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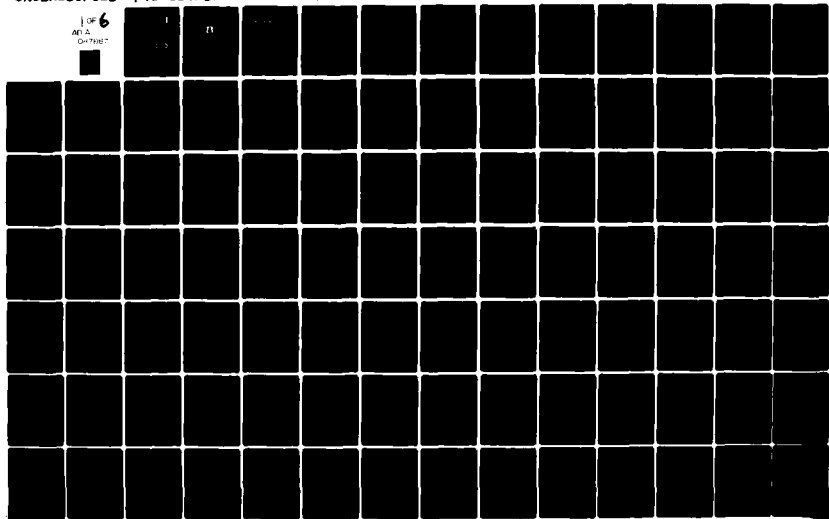
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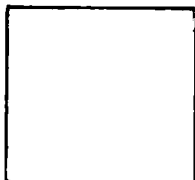
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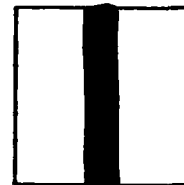
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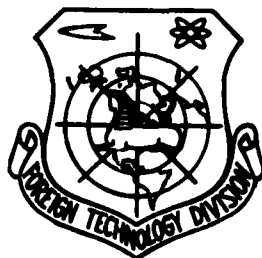
FOREIGN TECHNOLOGY DIVISION



ICING OF AIRCRAFT AND MEANS OF COMBATTING IT

By

O. K. Trunov



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ICING OF AIRCRAFT AND MEANS OF COMBATTING IT

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PREPARED BY:

TRANSLATION DIVISION
FOREIGN TECHNOLOGY DIVISION
WP-AFB, OHIO.

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U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	<i>А а</i>	A, a	Р р	<i>Р р</i>	R, r
Б б	<i>Б б</i>	B, b	С с	<i>С с</i>	S, s
В в	<i>В в</i>	V, v	Т т	<i>Т т</i>	T, t
Г г	<i>Г г</i>	G, g	У у	<i>У у</i>	U, u
Д д	<i>Д д</i>	D, d	Ф ф	<i>Ф ф</i>	F, f
Е е	<i>Е е</i>	Ye, ye; E, e*	Х х	<i>Х х</i>	Kh, kh
Ж ж	<i>Ж ж</i>	Zh, zh	Ц ц	<i>Ц ц</i>	Ts, ts
З з	<i>З з</i>	Z, z	Ч ч	<i>Ч ч</i>	Ch, ch
И и	<i>И и</i>	I, i	Ш ш	<i>Ш ш</i>	Sh, sh
Й й	<i>Й й</i>	Y, y	Щ щ	<i>Щ щ</i>	Shch, shch
К к	<i>К к</i>	K, k	Ъ ъ	<i>Ъ ъ</i>	"
Л л	<i>Л л</i>	L, l	Ы ы	<i>Ы ы</i>	Y, y
М м	<i>М м</i>	M, m	Ь ь	<i>Ь ь</i>	'
Н н	<i>Н н</i>	N, n	Э э	<i>Э э</i>	E, e
О о	<i>О о</i>	O, o	Ю ю	<i>Ю ю</i>	Yu, yu
П п	<i>П п</i>	P, p	Я я	<i>Я я</i>	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ë in Russian, transliterate as yë or ë.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	sinh ⁻¹
cos	cos	ch	cosh	arc ch	cosh ⁻¹
tg	tan	th	tanh	arc th	tanh ⁻¹
ctg	cot	cth	coth	arc cth	coth ⁻¹
sec	sec	sch	sech	arc sch	sech ⁻¹
cosec	csc	csch	csch	arc csch	csch ⁻¹

Russian English

rot curl
lg log

ICING OF AIRCRAFT AND MEANS OF COMBATTING IT.

O. K. Trunov.

Page 2.

The book acquaints the reader with physical and theoretical bases of the process of icing, meteorological conditions, which call this phenomenon in flight, and by the contemporary thermal and chemical means of deicing (de-icing systems), that are applied on passenger aircraft and helicopters.

In the book are examined also the methods of the selection of the basic parameters and calculation of the anti-icing electro- and air-heat systems; the effect of degree and form of icing on aircraft performance and technique of its piloting; the methods for aircraft testing in flight under conditions of icing and special feature/peculiarity of icing at rest of aircraft on the earth/ground.

The information given in the book, which relates to the practice

of flights under conditions of icing, and the presentation of remaining material on the basis of simple mathematical apparatus, makes it possible to recommend the book not only aeronautical engineers, workers of design bureaus and scientific research organizations, but also to technical flight personnel, which operates aircraft and helicopters.

Page 3.

Preface.

With the phenomenon of ice formation on the surface of aircraft the aviation for the first time clashed in the period when systematically began to be fulfilled flights in cloudiness.

Ice hazard consists in deterioration in the aerodynamic characteristics and flight aircraft quality/fineness ratios, reduction in the lift effectiveness of wing, increase in the head resistance, in deterioration in the stability and controllability. Besides this icing can cause the failure of the series/row of the most important aggregates/units and instruments and finally which is especially important, to upset the operation of engines. Experiment of jet flights showed that for turbojet engines is required the effective anti-icing protection.

In spite of the apparent specificity and the narrowness of the problem of icing, it encompasses a large quantity of diverse questions from the region of physics, meteorology, aerodynamics, thermodynamics, construction and operation of aircraft.

Initially primary attention was given to the so-called passive method of deicing, which was being reduced to the tendency to avoid in flight of such meteorological conditions which can cause icing. However, obvious insufficiency and inadequacy of this method already in the beginning of the 30's made it necessary to turn to the development of the special devices/equipment, shielding aircraft from icing.

The examination of the problem of aircraft icing as a whole was for the first time made in that published in Soviet authors' 1938 book "icing of air vessels" [24], and then in that left year after to N. V. Lebedev's work [10].

Subsequently in Soviet press/printing it did not appear the analogous generalizing works.

The first deicers were distant from perfection and they provided

only the execution of short-term flight under conditions of weak icing.

Page 4.

Further rapid development of aviation technology, task of operating the aircraft under any meteorological conditions (creation of the so-called "all-weather" aircraft) made it necessary to pay the most serious attention to development and design of effective and reliable de-icing systems.

For the resolution of this task was carried out large number of investigations and works both in the Soviet Union (A. Kh. Khragian, I. G. Pchelko, A. S. Zuyev, N. P. Fomin, R. Kh. Tenishev, L. M. Levin, I. P. Mazina K. Ye. Polissachuk, P. K. Dushkin, M. F. Belov et al.) and abroad (F. R. S. Taylor, M. Glauert, I. Langmuir, M. Tribus, N. Bergrun, I. S. Serafini, I. K. Hardy, D. Fraser, R. D. Crick, R. L. Messinger, etc.).

At present all aircraft, as a rule, are equipped by devices/equipment for protection from icing.

However, in spite of the extent of outfitting of aircraft, sharply increased in last 10-15 years, with anti-icing means and increase in their effectiveness, icing, as is shown by experiment,

continued to remain the factor on which depends substantially the safety and the regularity of flights.

This work does not pretend to the comprehensive presentation of all sides of the theme of aircraft icing, that at present virtually it cannot be made in the size of one book. The author only made the attempt to very briefly present the complex of the most basic questions, connected with this problem. The knowledge of these questions first of all is necessary for aviation specialists.

Taking into account also that with the problem of icing is connected the wide circle of the workers of aviation equipment (pilots, flight engineers, operation engineers, synoptics, students of aviation VUZ [BY308 - Institute of Higher Education], etc.), the author attempted to write such book which would be useful for persons with different profile of work and with different preparation.

The book in significant part is based on the results of investigations and tests, carried out by the author during period 1953-1963 in the state scientific research institute of Civil air fleet. In the book are used also the foreign materials, assembled by the author during his participation in the work of the international conferences, dedicated to the problem of the icing which took place in England in 1960 and 1961.

The author expresses gratitude to test pilots B. A. Anopov, V. I. Shutov, N. Ye. Karlash, G. A. Mikiforov and V. A. Filonovo, to fulfilled the series/row of complicated experiments under the severe conditions of icing, and also all participants in the combined in-flight studies as a result of which was obtained the valuable material, used in the book.

The author expresses deep gratitude to the colleagues of the institute A. A. Vodyana and V. M. Yushkevich for the great practical assistance, shown/rendered during the writing of the book, and also to L. L. Kerber and by V. A. Krupenikova, who made a series/row of valuable observations about the manuscript of the book.

Page 5.

Chapter I.

PHYSICS OF ICING.

1. Drop and sublimation icing.

The formation/education of the layer of ice on the surface of aircraft, streamlined with air flow, is caused by the presence in the atmosphere of water, which is found in different state.

In one case ice appears as a result of settling and freezing on the aircraft of the smallest drops of water, "floating" in air and retaining in the liquid state at minus temperatures. These droplets of supercooled water form (frequently together with ice crystals) those cloud forms which we observe in cold season. Therefore icing of this type occurs only in flight in the medium, which contains the supercooled drops (in clouds or, for example, under conditions of freezing rain).

In another case the icing is the consequence of the sublimation of the water vapor contained in the atmosphere, i.e., a consequence

of its transition directly into ice, passing liquid phase ¹.

FOOTNOTE ¹. In the courses of physics by sublimation usually is understood reverse process - the evaporation of solid body. We here adhere to the terminology, accepted in the literature on this question. ENDFOOTNOTE.

It is known that in the atmosphere the condensation of water vapor occurs usually on the surface of the smallest particles weighed in it - on the so-called condensation nuclei. As condensation nuclei in the atmosphere serve the smallest particles of hygroscopic substances - salts, dust, on which occurs the formation/education of embryonic droplets. Condensation occurs, if elasticity (pressure) of vapor in the atmosphere exceeds its elasticity above the surface of embryonic droplets formed on nuclei.

If in air are simultaneously condensation nuclei and ice crystals (or the freezing drops), then depending on the sizes/dimensions of those and others, and also depending on the temperature of air and saturation by its water vapors will occur either condensation of vapor, i.e., its transition into liquid state, or sublimation - transition of vapor directly into solid state.

Saturation vapor pressure near the surface of ice is less than above the surface of water. Because of this at sufficiently low minus temperatures despite the fact that air will not achieve saturation state with respect to water (its relative humidity less than 100%), it can prove to be oversaturated above the surface of ice and consequently will arise water vapor sublimation. This sublimation icing can occur in flight of aircraft in the cloudless atmosphere in such a case, when its surface on any reasons was preliminarily covered with the thin (frequently imperceptible for eyes) layer of ice.

Besides "drop" and sublimation icing ice formation can occur as a result of settling on the surface of the aircraft of crystals - phenomenon of "dry" icing. However, "dry" icing is encountered rarely and only under some specific conditions.

As early as 1937 A. Kh. Khrygian [22] showed that of two basic, qualitatively different forms of icing (drop and sublimation), the greatest danger for an aircraft represents the first and that the sublimation icing cannot be considerable. The practice of flights confirms this and it shows that the cases of serious icing are connected with the incidence/impingement of aircraft into the medium,

which contains the supercooled water drops.

2. Supercooled water in the atmosphere.

Any crystalline substance during heating converts/transfers into liquid state only at a completely specific melting point (and this pressure). From liquid state during cooling down to melting point the substance again converts/transfers into solid state. Under certain conditions the crystallization of liquid during cooling can be begun at temperature considerably lower than melting point. In this case, as they say, occurs supercooling of liquid. Experiments show that water, for example, can be supercooled to very low minus temperatures.

For crystallizing the liquid at temperature of its melting is required the series/row of the conditions: the presence in liquid of the nuclei (nuclei) of the crystallization with which begin the formation/education of solid phase, the continuous removal of the heat, which is isolated during crystallization, and finally, the temperature of liquid must be equal to melting point, and in this case the corresponding pressure.

The absence of any from these conditions will lead to the fact that the liquid at temperature of its melting will not be

crystallized.

During cooling crystallization does not begin evenly in entire volume of liquid, but it appears in its specific centers as which can serve the specks, the particles or other substances, and also finished crystal granules of this substance.

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The presence of such particles (crystallization nuclei) impedes supercooling liquid. Therefore, for example, thoroughly purified water better yields to supercooling than not purified. Laboratory investigations attest to the fact that in the considerable range of minus temperatures for crystallizing supercooled water is necessary the introduction to it of the finished crystals of ice. Opinion about the fact that supercooled water easily is crystallized with agitation or jolt, apparently, is based on the incorrect experimental setup. This phenomenon could occur in such a case, when on the walls of the container, higher than surface of supercooled water, were formed the particles of hoarfrost which with the agitation of container blew away from walls and is fallen down, immediately causing the crystallization of liquid. Obtaining (in small quantities) supercooled water with minus temperature of 2° - 4° C does not present serious difficulties. For this purpose thoroughly the container,

which then is closed by plug and undergoes cooling down to the temperature indicated. Supercooled water exhibits large stability to the different kind of mechanical effects, but if we introduce into container with supercooled water the small piece of ice, then it is possible to observe the rapidly occurring crystallization.

As noted above, the necessary condition of the freezing of water is the emergence of the nuclei of crystallization. At sufficiently low temperatures, in the absence of dirt particles the nuclei of crystallization can arise spontaneously via the random groupings of the molecules of water.

Such groupings continuously appear and disappear during the motion of molecules. With a temperature decrease the frequency of emergence and the sizes/dimensions of these groupings increase until appears the initial framework of crystal lattice, which subsequently is the nucleus (nucleus) of crystallization. English researcher Bigg [28] in 1953 on the basis of the experiments carried out by him assumed that the freezing of cloud drops at temperature of lower than -20°C occurs spontaneously and that the role of the crystallization nuclei under these conditions is insignificant.

However, this point of view repeatedly was disputed [47]. The majority of experiments shows that the crystallization nuclei play

active role in entire observed temperature range.

The spontaneous emergence of the crystallization nuclei obeys the law of probability and, therefore, the less the volume of supercooled liquid, the less the probability of their appearance. Laboratory investigations show that for the drops of water by diameter into several microns, which are found in air in suspension, the critical temperature, i.e., the temperature, with which occurs the spontaneous emergence of ice crystals, composes -40° , -41°C .

Page 8.

A decrease in the temperature in lower than this limit causes the rapid freezing of drops ¹.

FOOTNOTE ¹. Are known data about even deeper supercooling of drops. Rau [50] under laboratory conditions obtained supercooling small/fine drops to -72°C . ENDFOOTNOTE.

However, laboratory conditions always more or less differ from those conditions which occur in nature. Therefore at present it is not possible to indicate the limiting value of temperature, at which is possible the existence of nonfrozen water drops in the atmosphere and which consequently determines lower temperature boundary of

icing. Are known the cases of aircraft icing at high altitudes at very low temperatures. Thus, for instance, it was communicated [54] about the cases of aircraft icing above England at the height/altitude of 12000-13000 m at temperature of air from -61 to -65°C, as a result of which was assumed that the supercooled water in the atmosphere can exist to temperature of -65°C.

The second necessary condition of the freezing of water is the realization of the continuous heat removal. It is known that with the freezing 1 g of water occurs the liberation of the approximately/exemplarily 80 therms of heat. If crystallization would occur adiabatically, i.e., without heat exchange with the environment, then the heat isolating during crystallization would raise the temperature of liquid to 0°C and would avoid its further freezing.

For crystallizing the liquid at a specific melting point is required the constancy of this external pressure. Depending on the properties of substance, its molecular structure a change in the pressure affects in different ways the temperature of the crystallization of liquid. Thus, for instance, increase in the external pressure (to a definite limit) reduces the freezing point of water. This can be explained as follows. It is known that the physical properties of water, in comparison with the physical

properties of other substances, have a series/row of anomalies. In contrast to many other substances the water with freezing is expanded (its volume increases with freezing almost by 100/o); and during heating (to +4°C) is compressed, which is connected with changes in its molecular structure. The presence of strong external pressure impedes the expansion of water with freezing and, thus, it reduces the temperature, with which the water converts/transfers into solid state.

Under natural conditions, in the atmosphere, the supercooled water is found in the form of drops. The freezing point of the drop lower than freezing of the same liquid, placed into container, moreover this decrease is the function of a radius of drop. The less a radius, the lower the temperature, with which occurs the freezing of drop. This to a certain extent is explained by the existence of certain boost pressure, caused by the action of surface film on drop.

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The value of this pressure is directly proportional to surface tension and it is inversely proportional to a radius of drop. However, in spite of the very small sizes/dimensions of drops in clouds and fogs/mists, the value of the boost pressure appearing in them is clearly insufficient for a decrease in the temperature of

their freezing to the values observed in nature.

Investigations show that in cloud drops always are solutes. In particular, the chemical analysis of cloud tests/samples testifies about the presence in drops of chlorine ions, moreover with the decrease of sizes of drops (within certain limits) chlorine concentration increases. This fact also contributes to supercooling drops, since according to Raoult's law, the presence of solute reduces freezing point (it is known, for example, that the sea water freezes at lower temperature, than fresh).

But as a result of the fact that the concentration of the substances dissolved in cloud drops is very small ¹, its effect on lowering of the freezing point will substantially affect only in the initial stage of the formation/education of drops, since further increase in the drops due to condensation will lead to the decrease of the concentration in them of solutes.

FOOTNOTE ¹. A question about the reasons for existence in the atmosphere readily soluble of salts up to now is not completely studied. One should assume that their most probable source - world ocean. ENDFOOTNOTE.

The basic reason for the considerable supercooling of cloud

drops is connected, apparently, with the sharp decrease of the probability of the appearance of nuclei of crystallization as a result of small sizes/dimensions of drops. As noted earlier, at sufficiently low temperatures is possible the emergence of the spontaneous crystallization of liquid, moreover with the decrease of the volume of supercooled liquid decreases the probability of its crystallization. The decrease of the probability of the appearance of a crystal nucleus in a small volume of drop leads to the fact that the cloud drops whose sizes/dimensions are measured by the hundredth and thousandths of millimeter, can exist at low minus temperatures in the liquid state.

To crystallizing the drops exert the effect and other factors. To the freezing point of drops exerts influence their initial temperature. After the emergence of crystal nuclei the process of freezing will depend on rate of cooling of drop, since it will occur due to heat emission into the environment. If we take the drop of water with temperature of -10°C , then it is possible to determine which is sufficient to freeze $1/8$ parts of the drop so that heat of fusion isolated in this case would raise the temperature of remaining part to 0°C and would avoid its further freezing. As show experiments, during rapid cooling the freezing of drops begins outside, which makes it possible for them to interact with the environment as to crystals despite the fact that the internal part of

the drops is found even in the liquid state.

Page 10.

During slow cooling the freezing of drop begins within it, and complete freezing occurs at lower temperatures, than in the case of rapid cooling.

Ice formation on the surface of aircraft occurs as a result of the freezing of the encountering of supercooled water drops.

A question about the reasons for the rapid crystallization of the supercooled drops with their shock about the wing surface or about any other aircraft component up to now is not completely yet studied. As show experiments, supercooled water exhibits large stability with respect to various kinds of mechanical effects; therefore shocks and jolts by themselves do not cause its crystallization. Above were examined the conditions, necessary for crystallizing the supercooled liquid. If the cloud, in which flies the aircraft, consists not only of the supercooled water drops, but also contains ice crystals, or if on the surface of aircraft are at least smallest traces of hoarfrost, then the crystallization of supercooled water on the surface of aircraft will occur as a result of its contact with ice crystals.

However, also in the absence of ice crystals the freezing of the supercooled drops nevertheless occurs.

The experimental investigations of the effect of ultrasound on crystallization show that the ultrasound can accelerate crystallization sometimes hundreds times. Professor A. S. Irisov [8] assumed that the shocks of drops about the surface of aircraft are accompanied by the emergence of the ultrasonic waves which create the conditions, favorable for the nucleation of crystallization and freezing of the supercooled drops.

Finally, one should consider that independent of this on the skin of the aircraft almost always is located a sufficient quantity of particles of the contamination and dust which also can serve as the crystallization nuclei during incidence/impingement to the surface of the aircraft of supercooled drops of water from the atmosphere.

3. Ice formation on aircraft.

After using the principle of rotation of motion, let us examine the flow around the wing profile of aircraft of air flow, which

contains the supercooled water droplets.

As can be seen from Fig. 1.1, the airflow, which moves with subsonic speed, at certain distance before the wing profile is divided into two flows (demarcated by line MM), one of which passes on top, another - from below wing. After profile both flows are connected. This separation of flow is caused by the disturbances/perturbations from wing, which with the speed of sound are spread in surrounding air in different directions and, including against flow direction.

Page 11.

With the steady particle motion of the air, which flows around about the profile, they move over the specific trajectories - flow lines. The supercooled water droplets carried along by the forces of viscosity of air move at first also over flow lines. To as long as the flow line is rectilinear, the trajectory of drop virtually coincides with it. But in the section where the flow line is bent, going around profile, the drop moving/driving along it as a result of inertia attempts to preserve direction of its motion and begins to differ from flow line, being displaced towards profile.

If the amount of the inertial force proves to be sufficient in

order to overcome the forces of viscosity of air, then drop so will be deflected from flow line which will clash with wing. But if the inertial force is small, then drop insignificantly will be deflected from flow line and will pass past wing, without deposited on its surface.

Not all drops, which are located in the volume of air, which corresponds to the midsection of body, settle on its surface. As this was for the first time clearly shown by A. Kh. Khrgian, there is a specific zone, by the width of whose drops collide to by wing.

Let us assume that in the airflow, which flows around about the wing, are contained only very major drops. Then, as a result of the large force of inertia, trajectory of drops they are almost rectilinear and almost all drops, which are located before the wing, will settle on its surface. The width of the "zone of collision" δ_1 in this case will approach a profile thickness C , and ice accumulation will occur on large width (section E-E, Fig. 1.2).

When airflow contains only small/fine drops, then their only small part falls to the wing surface. Encounter wing there will be only those drops, which are located from axis M-M at the distances of smaller $\delta_2/2$.

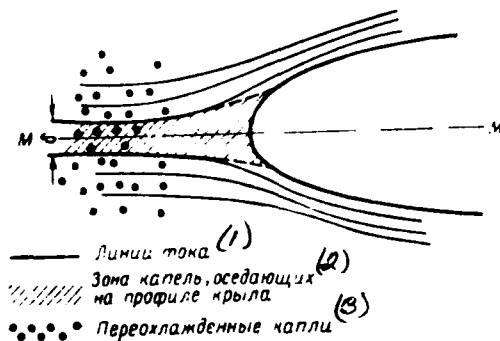


Fig. 1.1. Schematic of the flow around wing profile of air flow, which contains the supercooled drops.

Key: (1). Flow lines. (2). Zone of drops, which deposit on wing profile. (3). Supercooled drops.

Page 12.

Drops, which are located beyond the limits of the "zone of collision", as a result of small inertial forces will insufficiently differ from flow lines they will pass past profile. The width of the "zone of the collision" of such drops (δ_2) - small, ice formation occurs in the narrow section H-m. Is feasible the case when drops are so small that their trajectories virtually will coincide with flow lines. Then icing will not occur at all ($\delta=0$).

Under actual conditions in air usually there are drops of quite different sizes/dimensions. Therefore, for example, large drop, which is located at point B, can clash with the wing surface, and small drop despite the fact that it is located at point D, i.e., it is considerably nearer to axis M-M, it will pass past wing. The "zone of collision" (6) in this case will be determined by the edge trajectories of major drops.

Besides the size/dimension (mass) of drop and distance δ , large role in settlings of drops on the wing surface plays the air-stream velocity. The greater the speed of the motion of drops, the greater their quantity will deposit on profile per unit time. But an increase in the velocity also leads ~~also~~ to an increase in the forces of inertia of drops. If, for example, at what speed with profile collided only the major drops and the drops, which were being located at sufficiently close to the distance from the M-M axis, then with an increase in the velocity as a result of the increase of inertial forces, the latter can cause settling also small/fine drops which did not settle earlier. Thus with an increase in the velocity there occurs a deposit on the wing of even smaller drops and also drops ever more distant from axis M-M (i.e. grows/rises value δ).

Consequently, a quantity of ice, which is formed per unit time on the wing surface, is proportional to speed v^n , where $n > 1$.

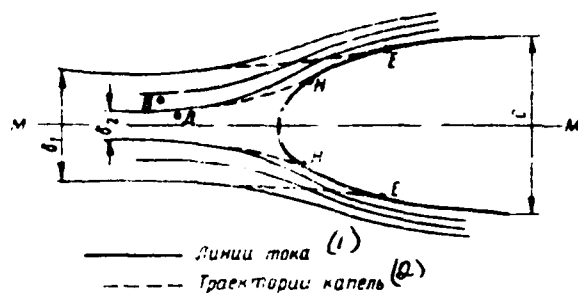


Fig. 1.2. Flow lines and trajectory of the drops of different sizes/dimensions during the flow around wing profile of air flow.

Key: (1). Flow lines. (2). Trajectories of drops.

Page 13.

The vertical velocity, i.e., the rate of an incidence/drop in the supercooled cloud drops, in comparison with the speed of aircraft, is so/such insignificant, which can be disregarded/neglected and considered drops as locating in suspension. For example, the vertical velocity of the drops with a radius of 10-20 μ does not exceed 1-5 cm/s, and only rain drops whose radius reaches 0.2-0.5 mm and more, possess considerable speeds incidences/drops.

If we consider cloud drops as locating in suspension, then it is obvious that collision with them they will test/experience only front/leading aircraft components. As is shown experiment, in the

majority of the cases ice formation occurs only on the frontal aircraft components, turned to the incident flow, whereas on the remaining surface of wing, tail assembly, fuselage ice accumulations occur rarely, for example, under conditions of supercooled rain.

Let us examine now as they affect the sizes/dimensions of wing profile the process of icing. It is not difficult to see that the profile of smaller thickness ices up more intensely than thick profile. This is explained by the fact that the separation of flow into upper and lower parts proceeds in thick profile on larger from it distance, than in thin profile. But this leads to the fact that the forces of air pressure caused by thick wing, which attempt to change rectilinear motion of drops, act on drops the more prolonged time (than in thin profile) and they manage certain part of the drops to deflect so, that the latter no longer deposit on the wing surface. Because of this on thick profile deposits a relatively smaller quantity of drops, than on thin profile. The practice of flights confirms that the thin wing profiles ice up more intensely than thick.

As noted, on the wing surface deposit only the drops, which are located in certain zone $\delta(\delta$ - this is distance at infinity, i.e., in the undisturbed region, between the extreme tangential trajectories of the drops of given size/dimension). All droplets of this

size/dimension which are included between extreme trajectories, encounter wing. The droplets which are located outside zone, limited by extreme trajectories, they pass by wing. If the cloud, in which occurs the flight, contains the droplets of identical size/dimension, then the quantity of water, which deposits per unit of the wingspan per unit time, will be determined by that quantity of water which is contained in cloud single thickness with the width, equal to δ .

The extreme tangential trajectories of drops determine also the so-called coefficient of settling (or capture), which is the relation of a real quantity of water, deposited on wing, to that quantity of water which is contained in the volume of air, passable by wing per unit time.

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If we consider that entire deposited on the wing surface water is converted into ice and freezes at impact point, then the quantity of ice, which is formed per unit time per unit of the length of wing (icing intensity) can be expressed by the following formula:

$$J = EWCV_{\infty} \quad (1.1)$$

where J - an icing intensity; E - complete coefficient of the settling; W - water content of clouds, i.e., a quantity of water in the form of drops, which is contained per unit of volume of the air;

C - profile thickness; U_∞ - speed of the undisturbed flow.

It is not difficult to see that the coefficient of settling $E = \delta/C$. Value E in equation (1.1) is called the complete coefficient of settling, since it is related to entire profile and is determined entire mass of water, which is precipitated per unit of the wingspan. But furthermore, it is frequently necessary also to know, what mass of water deposits per unit of the arc length of profile. For this is introduced the concept of the so-called local coefficient of settling E_l .

Let us designate the distance between two sufficiently close trajectories of drops in the undisturbed region through Δh (Fig. 1.3). Let these droplets be hit against wing profile at points A and B, the distance between which on the duct/contour of profile is equal to Δl . In this section (Δl) per unit time is precipitated out the quantity of water, equal to $\Delta M = U_\infty \cdot \Delta h \cdot W$. However, on the unit of arc length falls the quantity of water, equal to $\frac{\Delta M}{\Delta l} = \frac{U_\infty \cdot \Delta h \cdot W}{\Delta l}$. It is obvious that the ratio $\frac{\Delta M}{\Delta l}$ will determine icing intensity in section A-B. This sense during the unlimited approach of the trajectories of drops ($\Delta h \rightarrow 0$) in limit will be the local coefficient of settling E_l . Thus, value E_l determines the mass of ice, which is formed per unit of the arc length of profile, and the knowledge of this value makes it possible to calculate the distribution of icing intensity along wing

profile.

The calculation of the coefficient of settling and zone of ice accumulation on any body is reduced, as it follows from the preceding/previous reasonings, to computation of the trajectories of those drops which encounter this body. However, the calculation of the trajectories of drops requires the solution of the differential equations which determine the motion of drops about body.

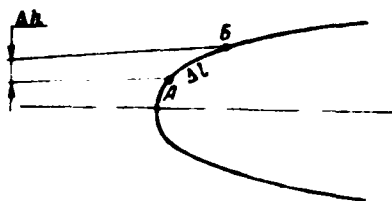


Fig. 1.3. To the determination of the concept about the local coefficient of settling.

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4. Equation of motion of drops.

As is known, on the body, streamlined with liquid (or gas), act the forces of inertia of the particles of the liquid, which move along the trajectories, which envelope body, and the forces of viscosity of liquid (force of internal friction).

When the forces of inertia of the particles of the liquid are small but to comparison with the forces of viscosity of medium, then can be disregarded/neglected, and then the head resistance of body is determined by Stokes's formula. For the body, which has the form of sphere, Stokes's formula takes the form:

$$F = 6\pi\mu v,$$

where F - resisting force to motion of the sphere; r - radius of the sphere; μ - coefficient of the dynamic viscosity of the liquid; v - speed of the motion of sphere relative to liquid.

For the water droplets (comparatively small size/dimension), which move in air with low speed, Stokes's formula sufficiently accurately determines the force of their head resistance.

In steady plane flow of the equation of motion of drop with the expression of the force of its resistance by Stokes's formula, it is possible to write in the form:

$$\left. \begin{aligned} m \frac{d^2x}{dt^2} &= 6\pi r \mu \left(V_x - \frac{dx}{dt} \right); \\ m \frac{d^2y}{dt^2} &= 6\pi r \mu \left(V_y - \frac{dy}{dt} \right). \end{aligned} \right\} \quad (1.2)$$

where x, y - coordinates of drop in the coordinate system, connected with the body; V_x, V_y - components of air-stream velocity; m - mass of the drop; r - radius of drop.

Precise integration of the equations indicated is impossible, since V_x, V_y - nonlinear functions of coordinates. Qualitative analysis and approximate solution of equations (initially for a cylinder) were carried out in the series/row of Soviet and foreign researchers' works [23], [36], [43], [33], [60], etc.

Equations (1.2) for simplification in calculations and determination of criteria relationships/ratios can be written in dimensionless form.

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Having used for this expression for the mass of the drop

$$m = 4/3 \pi r^3 \rho_k,$$

where ρ_k - density of drop and after dividing both parts of equation (1.2) on V_k after conversions we will obtain

$$\left. \begin{aligned} P \frac{dx}{dt} \frac{L}{V_k} &= \frac{dx}{dt} \frac{L}{V_k} \\ P \frac{dy}{dt} \frac{L}{V_k} &= \frac{dy}{dt} \frac{L}{V_k} \end{aligned} \right\} \quad (1.3)$$

where $P = \frac{r^2 V_k^2}{\rho_k L^2}$ - the parameter, which characterizes the inertia of the drop; L - significant dimension of the streamlined body; t - time.

FOOTNOTE : Parameter P in foreign ones and in some Soviet sources frequently is designated through K. ENDFOOTNOTE.

In the dimensionless form of equation (1.3) they can be converted:

$$\left. \begin{aligned} P^* \frac{dx}{dt} &= \frac{dx}{dt} \\ P^* \frac{dy}{dt} &= \frac{dy}{dt} \end{aligned} \right\} \quad (1.4)$$

where $\xi = x/L$ and $\eta = y/L$ — the coordinates of drop, in reference to the significant dimension of the body;

and β_x, β_y — ratio of components U_x and U_y to the speed of undisturbed flow U_∞

$\tau = \frac{t U_\infty}{L}$ — the dimensionless time, expressed depending on size/dimension of L and speed U_∞ , i.e. time unit is the time, necessary, so that the drop would cover a distance of L with a speed of U_∞

$\frac{d\tau}{d\xi}, \frac{d^2\tau}{d\xi^2}$ — respectively the first and second derivatives on τ .

In the indicated form the equations were for the first time written by Taylor. The mathematical expression of any phenomenon allows, without integrating differential equations, to come to light/detect/expose some special dimensionless quantities which characterize this phenomenon and serve as the so-called similarity criteria.

Equations (1.4) show that under the assumption of the validity of Stokes's formula the factors, which are determining the process of icing, are united in one dimensionless parameter P , which is the criterion of similarity of the trajectories of drops.

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Expression for parameter P can be represented in the relation

$$P = \frac{l_s}{L}$$

where

$$l_s = \frac{2}{9} \frac{V_\infty r^2 \rho_k}{\mu}$$

Latter/last value makes specific physical sense: l_s - this distance, which will pass the drop on inertia, being it is introduced into stagnant air with an initial velocity of V_∞ . Expression for l_s , it is possible to obtain, after integrating the equation

$$-m \frac{dV}{dt} = 6\pi r \mu V,$$

where m - a mass of the drop; V - speed of the motion of drop.

Obtained equations (1.4) are valid, as noted, with the expression of resisting force by Stokes's formula. However, for the sufficiently major drops the speeds of motion of which relative to air are essential, head resistance no longer should be determined from the formula of Stokes, since this can lead to considerable errors.

As is known, the resisting force to motion of body in liquid in general can be expressed as

$$F = C_x \rho l V^2.$$

where S - an area of so-called maximum cross section of the body; ρ - medium density; C_d - drag coefficient, being function of Reynolds number.

Expression analytical in general form for this function is unknown; therefore they usually use experimental data.

In work of I. P. Mazin [11] is brought the empirical formula obtained by him of resisting force

$$F = F_0(1 + 0,17Re^{2/3}),$$

where F_0 - resisting force according to the law of Stokes;

$Re = \frac{2rV}{\nu}$ - Reynolds number for a drop with a radius of r , moving/driving with the relative speed V in medium with kinematic modulus of viscosity ν .

Formula reflects well the amount of the real force, which acts on droplet in the range of Re numbers from 0 to 10^3 .

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In general, examining motion by three-dimensional and utilizing the proposed formula for resisting force, the equations of motion of

drop in dimensionless coordinates ξ , η , ζ can be written [12]:

$$\left. \begin{aligned} \xi &= \frac{1}{\rho} (W - V_0 F(\text{Re})) \\ \eta &= \frac{1}{\rho} (U - V_0 F(\text{Re})) \\ \zeta &= \frac{1}{\rho} (Z - V_0 F(\text{Re})) \end{aligned} \right\} \quad (1.5)$$

where $F(\text{Re}) = 1 - 0.17 \text{Re}^{-1} [(W - V_0)^2 + (U - V_0)^2 + (Z - V_0)^2]^{1/2}$

$\text{Re}_0 = \frac{2a}{V_0} \rho$ — Reynolds number for the drop, which moves with speed V_0 .

As we see, in this case of the trajectory of drops they are determined by already two dimensionless parameters P and Re_0 . Reynolds number Re_0 serves as the measure for deviation from Stokes' law of the forces, which act on drops. With $\text{Re}_0 = 0$ equation (1.5) they will be brought to equations (1.4).

5. Coefficient of settling and zone of ice accumulation.

For the calculation of the icing intensity of any body is required the knowledge of the coefficient of settling E . From theory it follows that all factors, which are determining precipitating the drops on body, can be brought to two dimensionless parameters, so-called criteria of similarity of the trajectories of drops, namely

to the inertia parameter P and Reynolds number Re_0 .

Frequently as the criteria of similarity of the trajectories of drops are utilized other combinations of the values, entering the expressions for P and Re_0 . For example, instead of the second parameter Re_0 sometimes is applied parameter $\phi = \frac{18\eta^2 V \cdot L}{\rho \mu^2}$ where ρ - an air density (it is not difficult to see that $\phi = Re^2_0/P$). The use/application of the parameter ϕ in many instances represents considerable convenience, since it does not depend on the size/dimension of drops and can be considered as the function of height/altitude, since with these sizes/dimensions of body and speed it depends only on density and viscosity of air.

Of two criteria of similarity of the trajectories of drops the dominant role plays parameter P , which characterizes the inertia of drops. However, the parameters ϕ and Re_0 play smaller role. Their value determines how real a forces, which act on droplets during their motion in air flow, they differ from the forces, computed from Stokes's formula.

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Since all values, which characterize precipitating the drops, are determined by two parameters indicated above, the coefficient of

settling E is also function P and ϕ (or Re_0). Dependence of E on P and ϕ is different for the bodies of various forms.

The calculation of the coefficients of settling was initially carried out for the bodies of a simpler form, than wing profile, and, in particular, for a cylinder, since with known approximation/approach the wing leading edge can be replaced by cylinder with the radius, equal to a radius of the forward section of the leading edge of an airfoil profile.

The method of replacing the wing profile by cylinder with some quantitative errors in consequence of which subsequently during calculations of de-icing systems was connected studied the phenomenon of the precipitation of drops directly on the wing of aircraft. The results of these investigations showed that the qualitative side of this phenomenon and the effect on it of different factors remain identical both for the cylinder and for a wing profile.

The radiation/emission of the phenomenon of the precipitation of drops on cylinder was of practical use also in connection with the fact that different meteorological instruments, which were being applied, for measuring the icing intensity, water content of clouds and sizes/dimensions of cloud drops, had receivers of cylindrical form.

Fig. 1.4 gives graph/curve, borrowed from work [30], which demonstrates for a round cylinder the dependence of the settling E full of coefficient on parameter P at different values ϕ . Here as the significant dimension L , entering parameters P and ϕ , serves a radius of cylinder.

As can be seen from graph/curve, the coefficient of settling grows/rises with an increase in parameter P , which will agree with the physical picture of phenomenon examined in § 3.

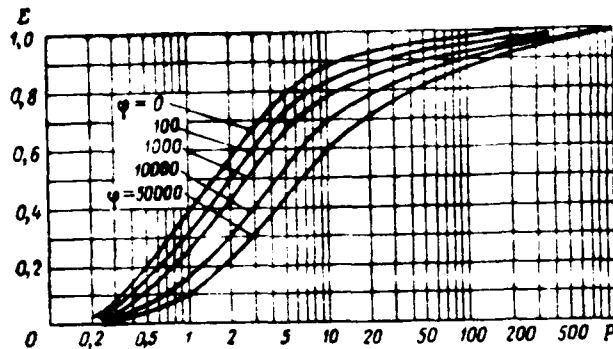


Fig. 1.4. Dependence of the total coefficient of settling of drops E on parameter P at the different values of the parameter ϕ for a round cylinder.

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Actually/really, with an increase in the air-stream velocity and with an increase in the size/dimension of drops parameter P increases, and consequently, increases coefficient E , entering formula (1.1), which is determining icing intensity. On the other hand, an increase in the radius of cylinder leads to decrease of P and respectively to a reduction in the coefficient of settling E , which decreases the icing intensity. However, the increase of parameter P cannot limitlessly increase E . The coefficient of settling, which is determining what part of the drops from the volume, passable by cylinder, encounters

the latter, naturally, there cannot be more than unity, $E=1$ will be in that limiting case when all drops deposit on body surface and when value δ is equal in magnitude to two radii of cylinder.

From graph/curve evident also that the curves of the coefficient of settling leave not the origin of coordinates, but the transverse axis of abscissas at certain value of P . This it indicates important the conclusion that with that determined P_{kp} the coefficient of settling is equal to zero and, therefore, the icing of body does not occur. Thus, the drops, for which parameter $P < P_{kp}$, they are not precipitated out on body. On the calculations of Langmuir [43] the precipitation of drops on cylinder occurs if and only if the parameter exceeds $P_{kp}=1/8$.

For flat/plane plate $P_{kp}=1/4$. For the wing profile of Zhukovskiy with the thickness ratio, equal to 150/o, on the data of L. M. Levin and N. R. Bergran [12] [26], values P_{kp} are within the limits from 0.0049 to 0.0078 with a change respectively in the lift coefficient c_y from 0 to 0.6.

Dependence on parameters P and ϕ the zone of ice accumulation is analogous the examined dependence of the coefficient of settling on these parameters. The zone of ice accumulation δ on cylinder can be defined by angle θ , as this is shown in Fig. 1.5.

FOOTNOTE 1. More precisely to speak about the zone of settling drops, which is frequently called the zone of capture, since as a result of the spreading of drops the zone of ice accumulation can be somewhat more. However, here and subsequently it is assumed that the drops freeze at the point of their incidence/drop i.e., the zone of ice accumulation it is determined by the tangential trajectories of drops. ENDFOOTNOTE.

Graph/curve in Fig. 1.6 shows that with an increase in parameter P the zone of ice accumulation (angle θ) grows/rises and it approaches its limit, equal to 1.57 radians, which corresponds to angle in 90° .

The determination of the coefficient of settling and zone of ice accumulation for an arbitrary wing profile is considerably more complex problem, than for a cylinder.

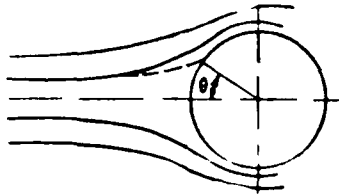


Fig. 1.5. To the determination of the concept of the zone of ice accumulation on cylinder from angle θ .

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If for a cylinder its form, sizes/dimensions and position in flow are determined only by the radius which enters into parameter P as significant dimension, then for a profile its form, sizes/dimensions (chord, thickness) and position in flow (angle of attack) cannot be expressed by any characteristic value. In connection with this for profiles of any type it is not possible to obtain the overall strict dependence of coefficient E on parameters P and ϕ (or Re_0).

At the same time the study of the precipitation of drops on different wing profiles showed that to the coefficient of settling E thickness ratio and its angle of attack exert insignificant effect, if thickness ratio is within the limits from 9 to 150/o, and angle of attack from 0 to 4° . This it allowed for a defined class of profiles

with the accuracy, acceptable for practical targets, to count the coefficient of settling depending only on parameters P and Re_0 . (For a profile the significant dimension, entering parameter P , it is chord).

The conclusion/output indicated was conducted by I. P. Mazin [12] on the basis of the generalization of the series/row of the calculations, carried out by N. K. Bergran and L. M. Levin ¹.

FOOTNOTE ¹. It should be noted that different configuration of the leading edge of an airfoil profile (the so-called completeness of nose/leading edge) with the same thickness ratio, of course, must affect the precipitation or drops. This follows from very physics of phenomenon. However, for the broad class of aviation profiles this effect both on the complete coefficient of settling E and to local coefficient E_{loc} near critical point is small. At the same time on a change in the local coefficient of settling in the arc of profile the configuration of nose/leading edge has considerable effect.

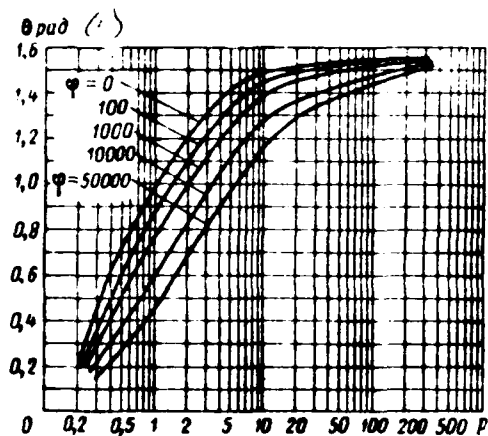


Fig. 1.6. Dependence of the zone of ice accumulation θ on round cylinder on parameter P at the different values of the parameter ϕ .

Key: (1). rad.

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For the calculations of the icing intensity of wing it is possible to use the graph/curve (Fig. 1.7), borrowed from work [12]. Graph/curve is valid in range indicated above of a change in the thickness ratio and angle of attack of profile. As can be seen from graph/curve, the dependence of the total coefficient of the settling of drops for a profile on parameters P and Re_0 in character is analogous the dependence, given in Fig. 1.4. With $Re_0 < 10$ the coefficient of settling E depends virtually on one parameter P .

Besides coefficient of E with the calculation of de-icing systems, and also in the experimental measurements of the intensity of icing it is frequently necessary to know local coefficient ϵ and especially its value near the critical point of profile.

Calculations show that from value Re_0 the coefficient of settling in section near the critical point of profile ($E_{\text{кр. точка}}$) depends to small degree and therefore in the first approximation, it is possible to consider that it is the function of one parameter P .

Dependence of λ on P for a profile is given in Fig. 1.8 [12]. This graph/curve it is possible to use for practical calculations.

For a cylinder analogous dependence is shown in Fig. 1.9.

Fig. 1.10 depicts a change in local coefficient in the duct/contour of cylinder. Values E_n , deposited/postponed to scale along the normal to cylinder for different angles θ , decrease from the maximum value equal to at critical point 0.62, to zero at the angle θ , equal to 57.3° .

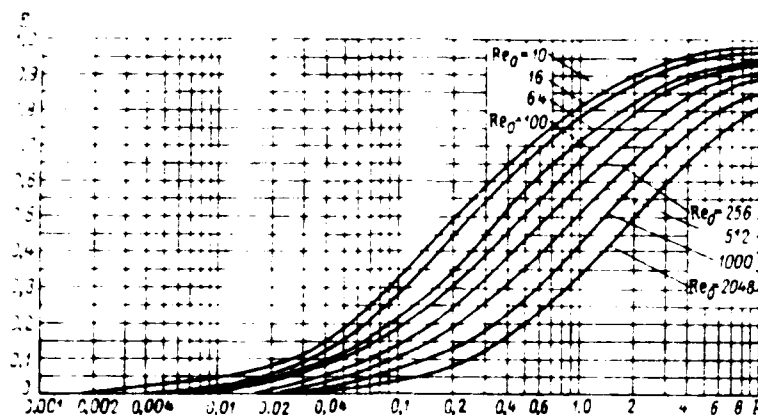


Fig. 1.7. Dependence of the total coefficient of settling of drops E for a profile on parameters P and Re_0 .

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Sometimes importantly it is to know also a change in the local coefficient of settling drops in the arc of profile. An example of this change for asymmetric Zhukovskiy profile is given in Fig. 1.11 1.

FOOTNOTE 1. Graph/curve is constructed according to N. R. Bergran's data [26]. ENDFOOTNOTE.

It is here along the axis of abscissas deposited/postponed for upper and pressure side of profile or ratio s/b , where s - a distance on

the duct/contour of profile from to the critical point; b - airfoil chord. Curve for $P=\infty$ corresponds to rectilinear trajectories of the drops; curve for a specific case in $P=0.125$ and $Re_0=64$ - curvilinear. As can be seen from graph/curve, the local coefficient of settling drops sharply decreases from leading edge on the arc of profile, reaching zero value at certain distance from leading edge. This distance determines point of contact of tangency on the profile of the extreme trajectory of drops, i.e., the zone of the capture of drops on profile.

With an increase in parameter P , as one would expect, the local coefficient of settling drops and the zone of their capture on profile grow/rise. On the profile in question for $P=\infty$ zone of capture (0.22 for lower and 0.32 for an upper surface) they coincide with the section of maximum profile thickness.

This change in the local coefficient of settling in the duct/contour of profile explains the form of ice outgrowth which initially is formed and which is characterized by the greatest thickness of ice at the critical point of the profile (where the values of local coefficient are maximum) ².

FOOTNOTE ². Subsequently in proportion to the increase of ice the form of profile is distorted and a change in the local coefficient no

longer corresponds to curve in Fig. 1.11. ENDFOOTNOTE.

Data about the local coefficient of settling make it possible to calculate the distribution of the intensity of the increase of ice according to the arc of profile and to determine the required energy content which must be conducted in each section of profile for its protection from icing.

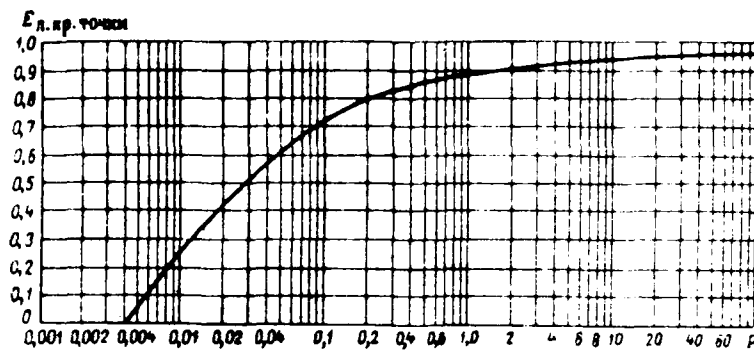


Fig. 1.8. Dependence of the local coefficient of settling drops near the critical point of profile ($E_{л.кр. точки}$) on parameter P .

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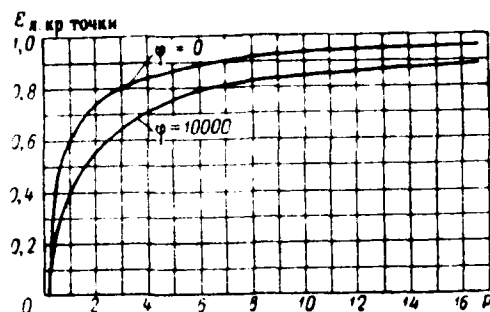


Fig. 1.9. Dependence of local coefficient of settling drops near critical point of cylinder on parameter P .

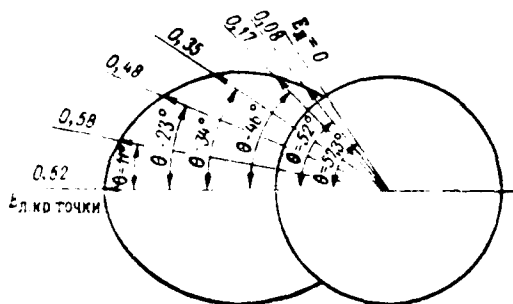


Fig. 1.10. Change in local coefficient of settling drops $E_л$ in duct/contour of cylinder with $R=1$ and $Re_0=0$.

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In more detail about the definition of the zones of ice accumulation and distribution of the local coefficient of settling speaks in chapter III. Here are given only several initial

graphs/curves for the calculation of zones settlements of drops. For aviation profiles most completely this question was examined in N. R. Bergran's work [26]. The differential equations, which are determining the trajectories of drops, were solved by N. R. Bergran with the aid of the computing device/equipment. The trajectory calculation of drops was conducted under the assumption of the incompressibility of air for a speed range from 160 to 560 km/h and drops in diameter from 20 to 100 μ . In calculations the chord length of profile varied from 0.75 to 9 m. These variable/alternating were introduced into the dimensionless parameters P and Re_0 ¹.

FOOTNOTE N. R. Bergran instead of parameter P used parameter ψ - "scale modulus/module", in this case $\psi = g\gamma_a/\gamma_k \cdot L/r$, where γ_a and γ_k - respectively the specific gravity/weights of air and drop.

It is not difficult to see that $\psi = Re_0/P$. In present work as almost in entire Soviet literature on this theme, there is used parameter P .
ENDFOOTNOTE.

To account for effect on the dimensionless parameters of the form of profile and angle of its attack N. R. Bergran examined the following five versions, given in table 1.

Fig. 1.12 gives those constructed on the basis of the data given

to table 1, overall dependences of the relative zone of the capture of drops s/b on parameters P and Re_0 for a symmetrical Zhukovskiy profile ($\bar{c}=150/o$).

In Fig. 1.7 and 1.8 were given graphs $E=f(P \text{ and } Re_0)$, obtained as a result of the trajectory calculations of drops during the flow around the Zhukovskiy profiles, and also profiles NACA-0.009, NACA-2215 and NACA 65₂-015.

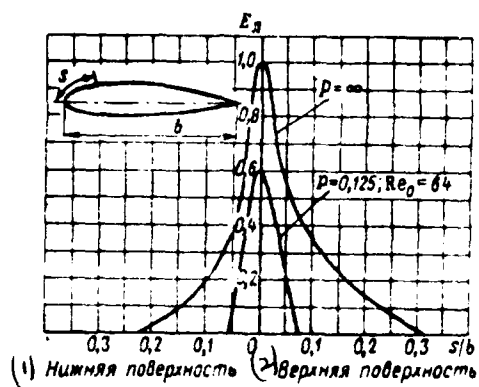
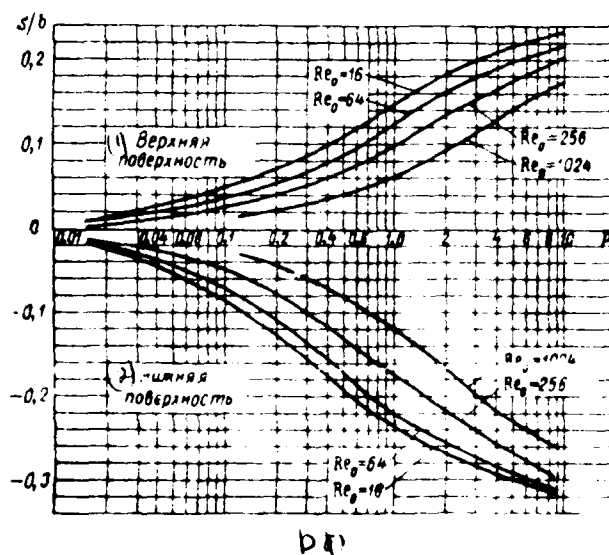
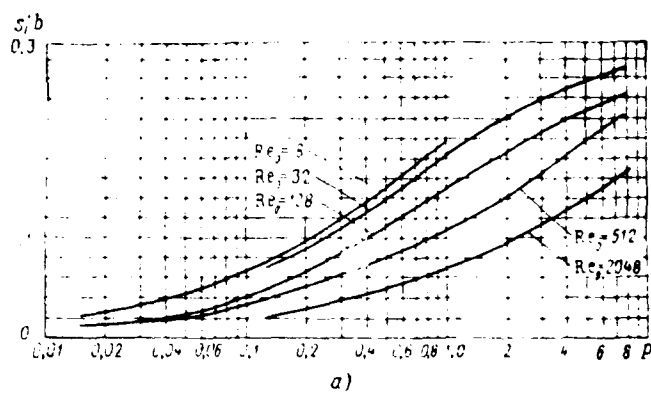


Fig. 1.11. Change in the local coefficient of settling drops E_s in the duct/contour of the curved profile of Zhukovskiy ($c_a = 0.44$, $\alpha = 0^\circ$, $\bar{c} = 150/o$).

Key: (1). Lower surface. (2). Upper surface.

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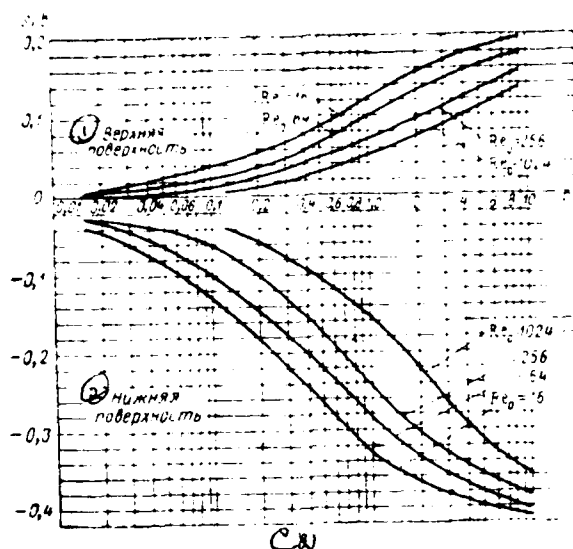


fig 1.12. Dependence of the relative zone of the capture of drops on parameters P and Re_0 for a symmetrical Zhukovskiy profile

$(c = 15^\circ/a)$.
 $a-c_y = 0, a=0^\circ, r/b=2.67, b-c_y=0.22, a=2^\circ, r/b=2.67, c-c_y=0.44, a=4^\circ, r/b=2.67$

Key: (1). Upper surface. (2). Lower surface.

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for the profiles, which sharply differ in form from those indicated, the dependence of the coefficient of settling on parameter P can be several different.

For example, let us examine (Fig. 1.13) settling drops on two profiles (A and B), with identical chord and thickness ratio, but by the different configuration of nose/leading edge. In this case let us assume that the drops are such large/coarse that their trajectories are rectilinear. It is not difficult to see that in profile with the pointed nose/leading edge the local coefficient of settling is less, since ratio $\Delta h/\Delta l$ for profile B is less than for profile A. However, the complete coefficient of settling for each profile is identical (under the condition of the straightness of the trajectories of drops). Under the normal conditions when the trajectories of drops are curvilinear, the local coefficient of settling drops in the pointed profile B will be also less; however, its complete coefficient of settling drops will be more than in profile A as a result of an increase in the "zone of collision" δ for the pointed profile. This it is necessary to keep in mind in the examination of the wedge-shaped and lens profiles, characteristic for supersonic aircraft.

During the study of the phenomenon of the precipitation of drops on different bodies it is necessary to remember that parameter P is the criterion of similarity of the trajectories of drops only for geometrically similar bodies (or at least for bodies with sufficiently close geometric form). For example, the precipitation of drops on two bodies, examined in Fig. 1.14, from which body B is the

part of another body A, occurs virtually equally with sufficiently high sizes/dimensions L_A and L_B . Meanwhile parameter P_B (body B) will be so much time more than parameter P_A (body A) in how often L_B is less L_A (, other conditions being equal,).

Table 1.

(1) Тип профиля	(2) Угол атаки α	(3) Радиус кривизны передней кромки в % хорды профиля (r/b)
(4) Симметричный профиль Жуковского с относительной толщиной 15%	0	0
(5) То же	2	0,22
(6) То же	4	0,44
(7) Изогнутый профиль Жуковского с относительной толщиной 15%	0	0,11
(8) Профиль NACA 65 ₂ -015 (симметричный)	4	0,44

Key: (1). Type of profile. (2). Angle of attack. (3). Radius of leading edge in o/o of airfoil chord (r/b) . (4). Symmetrical Zhukovskiy profile in thickness ratio 15o/o. (5). Then. (6). Bent Zhukovskiy profile with relative thickness 15o/o. (7). Profile NACA 65₂-015 (symmetrical).

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The determination of the coefficients of settling the bodies indicated with the use of dependence $E=f(P)$, obtained for the profiles of close in form, will bring in this case to errors.

6. Concept about the integral coefficient of settling and the mean radius of cloud drops.

Examining in the preceding/previous paragraph the coefficients of settling drops for cylinders and aviation profiles, we proceeded from the condition of the uniformity of cloud, i.e., we assumed that the medium, in which occurs the motion of this body, consists of the drops of identical size/dimension.

Under the actual conditions of cloud contain the drops of the most varied sizes/dimensions. If in this cloud is moved, for example, the wing of aircraft, then is obvious that the precipitation on the wing of the drops of different radius will occur differently. To each group of drops with an identical radius will correspond its specific coefficient of settling. However, as a whole the precipitation of drops on wing will be determined by certain total coefficient of settling drops, which is called integral and is designated by \tilde{E} [12]. For example, if in the cloud 40% water it is contained in drops from it is concealed by the radius for which the coefficient of settling is equal to E_1 , 30% of water in drops with the coefficient of settling E_2 , 25% - in drops with the coefficient of settling E_3 and 5% of water - in drops with coefficient of E_4 , then $\tilde{E} = 0.4 E_1 + 0.3 E_2 + 0.25 E_3 + 0.05 E_4$.

It is obvious that into the formula of the intensity of icing

(1.1) must enter the precisely integral coefficient of settling \tilde{E} .

For determining of \tilde{E} it is necessary to know the dependence of the coefficient of settling on the sizes/dimensions of drops, that it is possible to obtain, utilizing graphs of the preceding/previous paragraph, and also distribution of drops in cloud according to their sizes/dimensions.

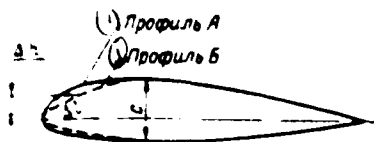


Fig. 1.13.

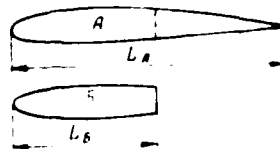


Fig. 1.14.

Fig. 1.13. For determination of effect of configuration of leading edge of an airfoil profile on local coefficient of settling drops.

Key: (1). profile.

Fig. 1.14. To explanation of precipitation of drops on bodies of different geometric form.

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The study of cloud microstructure of laminar forms showed that the spectral distribution of drops according to sizes/dimensions can be expressed by simple formula depending on the mean radius of drops

r_{cp} [12]:

$$n(r) = ar^b e^{-cr/r_{cp}}$$

where $n(r)$ - density of distribution of drops into 1 cm^3 of air

according to the sizes/dimensions; a - constant.

By r_p is understood arithmetic mean radius (i.e. $r_p = \frac{\sum r_i n_i}{\sum n_i}$), where n_i - a number of drops with a radius of r_i ¹.

FOOTNOTE 1. As showed investigations [1], this formula is valid also for convective clouds. ENDFOOTNOTE.

The use of the formula indicated and dependences of the coefficients of settling on parameter P , into which enters the size/dimension of drops, made it possible to calculate [12] the integral complete coefficient of settling drops \tilde{E} and integral local coefficient of settling drops near critical point (E_{integral}) for the 5 aviation profiles examined in Section in thickness ratio from 9 to 150/o.

Fig. 1.15 and 1.16 give the graphs/curves on which \tilde{E} and E_{integral} are given in dependence on the chord length of profile for two values of true airspeed (300 and 600 km/h) and two values of the mean radius of drops (4 and 8 μ). A change of the integral local coefficient of settling in dependence on speed is shown in Fig. 1.17.

These graphs/curves can be used with acceptable accuracy for the majority of practical calculations of the icing intensity of aviation profiles.

It should be noted that it is possible and not to introduce the concept of the integral coefficient of settling. In this case into the formula of the intensity of icing (1.1) must enter the coefficient of settling (complete or local), determined for those drops in which is contained the base mass of water of cloud. However, this method can be conjugated/combined with some errors during the calculation of icing intensity.

7. Icing at the high supersonic speeds of flight.

Air-stream velocity directly enters into the formula of the intensity of icing (1.1). But furthermore with an increase in the velocity increases the coefficient of settling drops E , which leads to even more rapid increase of ice.

The calculations of the coefficients of settling drops for cylinders and aviation profiles, examined above, were made under the assumption that air was incompressible. Meanwhile at the sufficiently high flight velocities in air appear such pressure differences which noticeably change its density.

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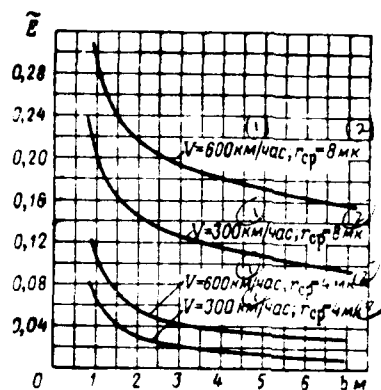


Fig. 1.15. Dependence of integral total coefficient of settling of drops \tilde{E} for aviation profile from chord length.

Key: (1) . km/h. (2) . μ .

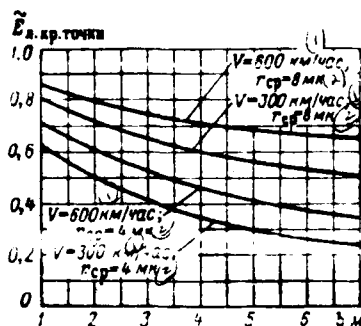


Fig. 1.16.

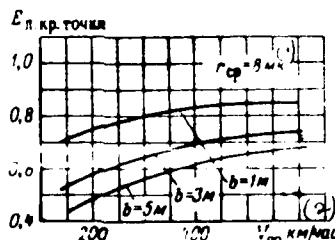


Fig. 1.17.

Fig. 1.16. Dependence of integral local coefficient of settling drops $\tilde{E}_{kp, \text{tochny}}$ near critical point of profile on chord length.

Key: (1). km/h. (2). μ .

Fig. 1.17. Dependence of integral local coefficient of settling drops $\tilde{E}_{\text{л.п. точки}}$ near critical point of profile on flight speed.

Key: (1). μ . (2). km/h.

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Because of this it is necessary to explain, as the phenomenon of the compressibility of air it will affect settling drops.

From airfoil theory, which moves with subsonic speed, it is known that the flow around profile in compressible liquid corresponds to flow at the high angle of attack of the thickened profile in the incompressible fluid.

Relative thickness of this fictitious profile \bar{c}_ϕ and its angle of attack are connected with the thickness ratio of this profile \bar{c} and its angle of attack α with relationships/ratios 1:

$$\bar{c}_\phi = \frac{\bar{c}}{\sqrt{1-M^2}}, \quad \alpha_\phi = \frac{\alpha}{\sqrt{1-M^2}}$$

where Mach number is the relation to air-stream velocity to the speed of sound.

FOOTNOTE 1. These relationships/ratios from the airfoil theory of Prandtl-Glauert, valid only for thin profiles and low angles of attack, are given here only for the explanation of the physical essence of phenomenon. More fully the theory of compressibility effect was developed by Soviet academician S. A. Khristianovich.

ENDFOOTNOTE.

Since the thick profile (see g 3) ices up, other conditions being equal, is less intensely, than thin, then hence it follows that the compressibility of air decreases the coefficient of settling drops.

From this correct actually position some researchers made incorrect practical the conclusion that the decrease of the coefficient of settling as a result of the compressibility effect of air can to a considerable degree compensate an increase in the icing intensity with an increase in the speed. The comparison of the trajectories of drops in compressed air flow with the trajectories of drops in the incompressible air showed that the compressibility effect is comparatively small and for solving many practical tasks it can be disregarded/neglected. Is explained this by the following:

The compressibility effect on flow line becomes apparent perceptibly only near body, for example, for a cylinder at a distance, exceeding its radius, compressibility no longer affect the flow line. On the other hand, the compressibility effect virtually does not appear for the center section of the flow lines, i.e., near critical point. Because of this the drops, which possess large inertia, do not manage to change their motion and thus effect on their trajectory of the compressibility of air is very insignificant. However, The small/fine drops, which deposit on body, always are arranged/located in the center section of air flow, i.e., where the compressibility effect is also insignificant. Compressibility has perceptible effect only on the drops of average sizes (with average values of parameter P). Fig. 1.18 shows compressibility effect on the complete coefficient of settling depending on parameter P for a round cylinder.

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As can be seen from figure, $E_{\text{ср}}$ is less $E_{\text{нечр}}$ it is maximal to 30/o (calculations are carried out at the value of Mach number, close to critical). For a profile the decrease of the total coefficient of settling of drops as a result of the compressibility of air can be somewhat greater. However, to the local coefficient of settling near

critical point compressibility virtually does not affect,

Thus, the decrease caused by compressibility of the coefficient of settling of drops will not show/render the considerable counteraction to the increase of the intensity of icing with an increase in the velocity of flight.

However, upon reaching of sufficiently high speeds is observed another phenomenon, which blocks further icing.

Let us write the known equation of Bernoulli for air (taking into account its compressibility):

$$\frac{V_1^2}{2} + \frac{k}{k-1} \cdot \frac{p_1}{\rho_1} = \frac{V_2^2}{2} + \frac{k}{k-1} \cdot \frac{p_2}{\rho_2} \quad (1.6)$$

Here V_1 and V_2 - with respect to the air speed in some two sections, isolated in air flow; p_1 and p_2 - pressure; ρ_1 and ρ_2 - air density in the sections; $K = c_p/c_v$ - relation of heat capacity of air at constant pressure (c_p) to its heat capacity at a constant volume (c_v).

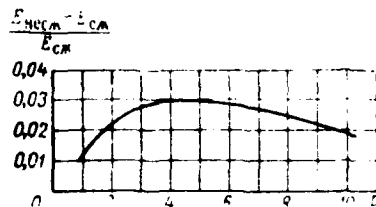


Fig. 1.18. Compressibility effect of air on the complete coefficient of settling drops depending on parameter P for a round cylinder.

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After using the equation of state of gas in the form $p = g\rho RT$ (where g - acceleration of gravity, R - gas constant, T - absolute temperature), equation (1.6), can be converted to the following form:

$$\frac{V_1^2}{2g} + \frac{k}{k-1} RT_1 = \frac{V_2^2}{2g} + \frac{k}{k-1} RT_2 \quad (1.7)$$

or, transferring/translating the terms of equation into the thermal units

$$A \frac{V_1^2}{2g} + \frac{k}{k-1} ART_1 = A \frac{V_2^2}{2g} + \frac{k}{k-1} ART_2, \quad (1.8)$$

where A - heat equivalent of mechanical work.

From thermodynamics it is known that $AR = c_p - c_v$, whence $\frac{k}{k-1} AR = c_p$. Utilizing this relationship/ratio, equation (1.8) in the final form

$$T_1 + \frac{AV_1^2}{2gc_p} = T_2 + \frac{AV_2^2}{2gc_p} \quad (1.9)^*$$

FOOTNOTE 1. Equations (1.8) and (1.9) are only different expressions of the law of conservation of energy for the moving/driving gas. Was here used in the beginning the equation of Bernoulli as more familiar to readers' majority. ENDFOOTNOTE.

Let the first section be is selected at sufficiently large distance from profile, and the second at its critical point where the flow completely is braked, i.e., $V_2=0$. Then

$$T_2 - T_1 = \frac{AV_1^2}{2gc_p}, \quad (1.10)$$

i.e., during the total stagnation of the air, which was moving at a rate of V , occurs its heating to value $\frac{AV^2}{2gc_p}$, the temperature of air at the critical point of profile will be more than the temperature of surrounding air (T_1) to the value indicated.

Formula (1.10), which is determining the so-called kinetic heating, can be simplified, after substituting into it the values of the corresponding values: $A=1/427 \text{ kcal/kg}\cdot\text{m}$; $c_p=0.24 \text{ kcal/kg}\cdot\text{deg}$ and $g=9.81 \text{ m/s}^2$.

Taking into account this substitution we will obtain

$$\Delta T = T_2 - T_1 = \frac{V^2}{2000} \text{ } ^\circ\text{C.} \quad (1.11)$$

As is known, air compression in the absence of heat exchange with the environment (adiabatic compression) is accompanied by an increase in its temperature. the rapidly elapsing processes of air compression in practice can be considered very close to adiabatic ones. Braking airflow leads to its compression and connected with this increase in the temperature. It is obvious that at the critical point where the flow completely is braked, heating air will be greatest. However, also on the lateral surface of the profile where the air speed can exceed the speed of the incident undisturbed flow, heating air occurs.

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This is explained by the fact that during flow in body surface is formed the thin boundary layer of the stagnated air whose emergence is caused by the viscous forces. Because of the fact that the air speed in the layer, directly adjacent to body surface less than in the more distant layer, occurs internal friction, which leads to heat liberation and increase in the temperature of boundary-layer air.

Thus, with an increase in the flight speed, on one hand, occurs

an increase in the icing intensity, and with another, there is kinetic heating of the surface of aircraft as a result of compression and friction of contrary air flow.

It is obvious in such a case, when the temperature of the surface of aircraft proves to be as a result of heating by positive, ice formation does not occur. On this in their time were based the assumptions relative to that for the aircraft, which were being operated on speeds on the order of 700 km/h, icing it will not represent danger. However, this proved to be inaccurate.

Formula (1.11) for convenience it is easy to convert as follows:

$$\Delta T \approx 0.38 \left(\frac{V}{100} \right)^2, \quad (1.12)$$

where V - speed of aircraft in km/h.

From this formula it is evident that for the flight speeds, smaller 300 km/h, heating leading wing edge will not exceed $\sim 3.5^\circ\text{C}$.

Formula (1.12) gives the sufficiently close to reality value of kinetic heating at the critical point of profile in flight in so-called "dry" air (out of clouds). However, under conditions of icing the value of kinetic heating will be considerably less.

8. On the possibility of icing at supersonic flight speeds.

From the previous it follows that the greater the flight speed, that at lower temperature of surrounding air must occur aircraft icing. for supersonic speeds the kinetic heating of the surface of aircraft is so already high that the icing is possible only at temperature of surrounding air of -35° -- -40°C .

There are different points of view about the possibility of icing at supersonic flight speeds. In the opinion of some researchers [53] rhombiform and wedge-shaped profiles can undergo drop icing to Mach numbers, equal to 1.4 and even 1.8. On the other hand, for example, in work [12] is made the conclusion that the aircraft icing at supersonic flight speed due to settling of the supercooled water drops is virtually impossible.

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The basis for this conclusion/output served as the author the works indicated initial data on liquid-water content and cloud microstructure, existing at low temperatures of surrounding air.

Actually/really, theoretical calculations show that in flight with supersonic speed, in order to compensate the evaporation of the

moisture depositing on profile, is required the liquid-water content of droplet cloud on the order of 0.1 g/m^3 . The author of work [12] proceeded from the fact that water content of clouds with temperatures of -35 -- -40°C is less than the given value, but the radius of cloud drops does not exceed 5μ .

However, as this is shown below, the values of liquid-water content at temperature of air of -30°C in one percent of the cases can reach approximately 0.3 g/m^3 ¹.

FOOTNOTE ¹. This numeral is recommended as calculated during the design of the de-icing systems (see Chapter III). ENDFOOTNOTE.

This it indicates that also at lower temperatures is possible the existence of supercooled clouds with the liquid-water content, which considerably exceeds 0.1 g/m^3 , that also is confirmed by practice.

The recorded cases of icing (in flight at subsonic speeds) show that intense ice formation on the surface of aircraft as a result of settling of the supercooled drops is possible at temperature of surrounding air of -40°C and even it is lower.

In particular, one of the aircraft of Il-18 in flight through Atlantic underwent strong and prolonged icing at temperature of

surrounding air within the limits from -44 to -46°C . In this case the average/mean liquid-water content was not less than 0.5 g/m^3 .

Thus, at present it is possible to only assert that at supersonic flight speeds the cases of drop icing will be extremely rare ².

FOOTNOTE ². Should be considered also the possibility of crystal icing. ENDFOOTNOTE.

This however does not indicate that the anti-icing protection for a supersonic aircraft is not required. The execution of reduction and landing approach is connected for a supersonic aircraft with transition to such speeds, at which the probability of icing also is great as for low-speed piston-engined aircraft. And therefore however short-term there was the flight of supersonic aircraft at low speeds, for it is also necessary sufficiently powerful/thick and reliable de-icing system.

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Chapter II.

METEOROLOGICAL CONDITIONS OF ICING.

1. Basic meteorological factors, which affect icing.

Meteorological factors in different ways affect the process of aircraft icing. Liquid-water content directly determines the speed of the increase of ice. The temperature of air and the size/dimension of drops define mainly the type (form) of icing. At the same time the size/dimension of the drops through the coefficient of settling affects icing intensity. Finally, the three-dimensional/space extent of the zone of icing together with its intensity characterizes the quantity of ice which can be formed on aircraft.

Temperature of air.

Temperature of air - one of the basic factors, which are determining the phenomenon of icing. Ice formation on the surface of aircraft occurs at temperature of surrounding air of lower than 0°C moreover the minus temperatures, with which is possible the icing.

oscillate in the large limits: from values, close to 0°C , to the values, which reach -40°C it is below.

There is a specific temperature range, for which the probability of icing is greatest. Statistics shows that a great quantity of cases of aircraft icing proceeds at temperatures of air in gap/interval from 0 to -20°C , and in particular from 0 to -10°C . Icing at lower temperatures occurs considerably less often. The statistical data, assembled by central aerological observatory during the last few years above the territory of the Soviet Union, also show that the supercooled clouds, which call icing, are encountered to -40°C . In this case the frequency of their appearance at temperature of air of lower than -35°C comprises less than 100/o cases. In range from 0° to -10°C the drop supercooled clouds are encountered into 800/o of cases.

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Are known the cases of drop icing in powerful/thick cumulonimbus clouds at temperatures of air within the limits from -40° to -50°C . Thus, for instance, on 14 August, 1961, in area g. Voronezh with the execution of experimental flight the aircraft of Tu-104 at the height/altitude of 10500 m underwent intense icing in the upper part of the powerful/thick cumulonimbus cloud at temperature of

surrounding air of -48°C . In other case the aircraft of Tu-104 met icing at the height/altitude of 10100 m at temperature of -47°C (flight was accomplished on 22 July, 1961, in area g. vologda).

As noted in the beginning of the preceding/previous chapter, was noted aircraft icing at even lower temperatures of air (-65°C). However, the limitedness of the information about such cases does not make it possible to make the completely specific conclusions relative to the mechanism of icing at temperatures indicated.

The icing of individual parts of the power plants is possible at positive temperatures. For example, the icing of carburetor frequently appears at temperature of surrounding air considerably higher than 0° , which is connected with a temperature decrease as a result of evaporation. There is also an opinion about the fact that if the aircraft completes takeoff under conditions of precipitation of rain or melting snow at positive temperature, very close to 0°C , then the surface of aircraft is covered/coated with the water film which evaporates during takeoff, is cooled and it can freeze, having formed a thin ice crust.

Air humidity.

Aircraft icing is connected with the specific air humidity.

"humidity" or "dryness" of air is determined not by the absolute quantity of water vapor, which are contained per unit of volume of air (absolute humidity a in g/m^3), but that, how air is close to saturation state. A quantity of vapor (A in g/m^3), necessary for saturating a unit of the volume of air, is changed depending on temperature, increasing with an increase in the latter, and vice versa, decreasing with its decrease. The degree of the saturation of air by water vapor, as is known, it is characterized by the relative humidity - ratio a/A , expressed usually in percentages. With a temperature decrease relative humidity increases, and air approaches saturation state. Observations show that the relative humidity with icing composes 80-100%. Specific humidity, i.e., a quantity of water vapor, which is contained in 1 kg of humid air, in conditions of icing usually exceeds 1 g/kg.

An increase in the relative or specific humidity with height/altitude testifies about conditions favorable for icing.

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Liquid-water content of supercooled clouds.

As already repeatedly it was noted, ice formation on aircraft is directly connected with the presence in the atmosphere of the

supercooled water drops. If absolute humidity characterizes liquid-water content, that is found in vaporous state ¹, then liquid-water content determines the content per unit of volume of air of water, which is found in the drop-forming state.

FOOTNOTE In practice vapor frequently is called the accumulation of the smallest drops of water. water vapor - invisible gas without color and without odor. ENDFOOTNOTE.

Liquid-water content is one of the most important factors of the icing, to study of which during the last few years was devoted a considerable number of works [13], [14], [6], [7], [45], ^[49][27], [24], etc.

This is fully understandable, since the quantity of the moisture, condensed in the form of drops, that contains per unit of volume of air, it directly affects the rate of formation of ice on aircraft.

The various forms of cloudiness are characterized by the values of liquid-water content equal for them. But also in by one and the same of cloudiness the values of liquid-water content can oscillate extremely sharply. Connection/communication of liquid-water content with different meteorological parameters and with the mechanism of

the formation/education of clouds is up to now studied little. It is revealed only, that the liquid-water content depends substantially from three parameters: temperature, temperature gradient and height/altitude from lower cloud base. Insufficiently still there is also data about the values of liquid-water content at low temperatures of air, which impedes the selection of the design conditions of icing, i.e., the conditions to which must be calculated the de-icing system of aircraft.

The work on the study of the liquid-water content of supercooled clouds, which were being carried out in the Soviet Union (mainly by central aerological observatory) and abroad (V. Lewis, K. Pettit et al.), on the whole gives the identical picture of the values of liquid-water content. Thus, for instance, according to data of TSAO in the clouds of laminar forms the maximum of the recurrence of the values of the liquid-water content occurs for $\sim 0.1 \text{ g/m}^3$, and its maximum values reach 1.6 g/m^3 .

According to Canadian researcher K. Pettit's data [49] the maximum of recurrence also corresponds 0.1 g/m^3 , and the maximum values of $\sim 1.4 \text{ g/m}^3$.

According to V. Lewis's data [45] in stratus and stratocumulus clouds the maximum of recurrence is within the limits of $0.1-0.19$

g/m^3 , but maximum values do not exceed 1 g/m^3 , in this case into 95% of cases the liquid-water content comprises less than 0.5 g/m^3 . It should be noted that V. Lewis's data are based on the considerably smaller number of observations (372 cases), than data of TAO and K. Pettit which connect thousand and hundreds of measurements.

In the supercooled cumulus and cumulonimbus clouds the liquid-water content can reach considerably larger values. The maximum of recurrence for these clouds falls to $\sim 0.2 \text{ g/m}^3$, maximum values approach 2 g/m^3 , but into 95% of cases liquid-water content comprises less than 0.9 g/m^3 (according to V. Lewis's data).

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Systematized data on the cumulonimbus clouds it is insufficient for the confident conclusion/output about the possible values in them of liquid-water content. However, according to separate mainly indirect observations it is possible to assume that these values can considerably exceed Lewis's data. In this case it is necessary to keep in mind that the "instantaneous" values of liquid-water content can be much more than the values, averaged in sections, extent into several kilometers.

In the literature there are communications/reports about the

recorded values of the liquid-water content of supercooled clouds on the order of 3-5 g/m³ and even it is more. For example, in case given at the end of this chapter of exclusively intense icing of aircraft "Vanguard" average/mean liquid-water content within the time of 10-15 min (during which continued icing) was approximately 3.6 g/m³.

Over a number of years central aerological observatory carried out the collection of systematic data about water content of clouds on the points/items of aircraft sounding, located in different points of the territory of the Soviet Union. As a result of this was assembled the vast material on the liquid-water content of supercooled clouds, which made it possible to obtain sufficiently specific data about the frequency of the recurrence of liquid-water content depending on the temperature of air. In the examination of the obtained material one should consider that the measurements of liquid-water content, which were being conducted in the majority of the cases with the aid of the instrument of construction/design V. A. Zaytsev [7], lasted by 5-10 s; therefore the obtained results approach "instantaneous" values of liquid-water content.

Fig. 2.1 gives the isopleths of the recurrence of water content of clouds, in percentages of overall quantity of cases (5785) depending on the temperature of air. Graph/curve is constructed on the basis of processing data indicated above and is related to the

conditions of the European USSR. As is evident, the values of liquid-water content sharply decrease with a decrease in the temperature of surrounding air. Thus, for instance, for the isopleth, which corresponds to one percent of the cases, liquid-water content for a temperature range from -0.1 to -5°C is within the limits of 0.41 - 0.45 g/m^3 , and at temperatures from -15.1 to -20°C liquid-water content is 0.11 - 0.15 g/m^3 .

Fig. 2.2 gives the dependence of the no/c quantiles ¹ of water content of clouds on the temperature of surrounding air.

FOOTNOTE ¹. By the quantile or the assigned percentage is understood such value of variable quantity at which in the percentage of the cases indicated the encountered values of the value of less than data. ENDFOOTNOTE.

Let us examine, for example, ninety-percent quantile which shows that into 90o/o of cases for each temperature range of surrounding air the observed values of liquid-water content were less than the values, corresponding to this curve.

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So, with temperatures of surrounding air in limits from minus

0.1 to -5°C into 90o/o of cases liquid-water content did not exceed 0.4 g/m^3 , and at temperatures from -20.1 to -25°C liquid-water content comprised not more than 0.2 g/m^3 . This graph/curve makes it possible to refine the proposed design conditions of icing [18].

It is necessary to keep in mind that statistical data on the basis of which are constructed Fig. 2.1 and 2.2, are not, by certainly exhausting. In particular, they are insufficient for the clouds of convective development and do not cover the geographical special features/peculiarities of different areas.

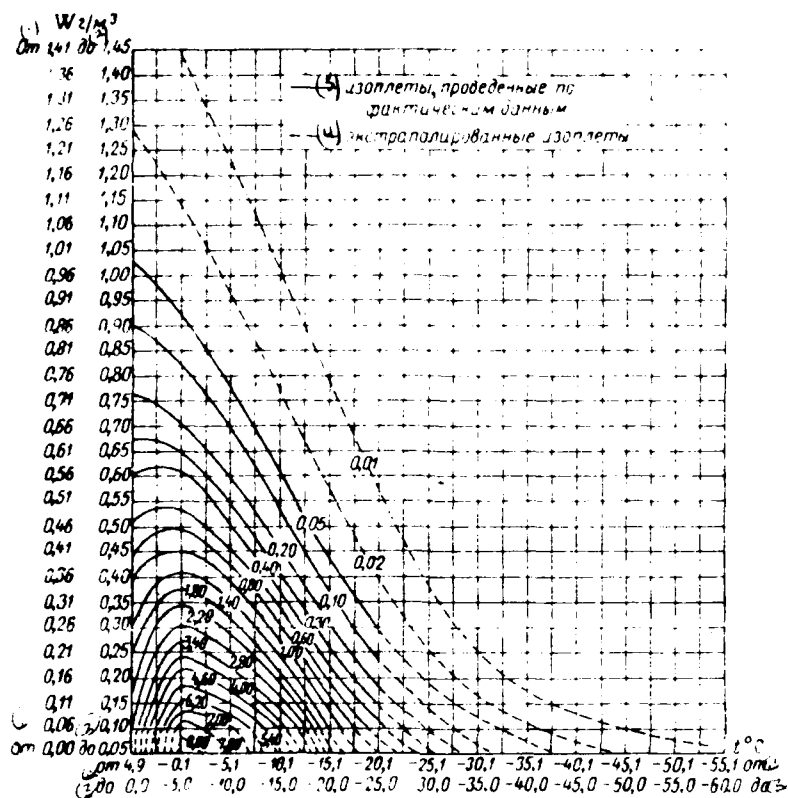


Fig. 2.1. Isopleths of the recurrence of water content of clouds.

Key: (1). From. (2). to. (3). isopleths, carried out by actual data.
(4). extrapolated isopleths.

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Comparisons with the published foreign materials, and also observations of icing intensity show that in areas above the oceans

and in tropical areas the liquid-water content can considerably exceed the values of liquid-water content for the territories of the Soviet Union.

Cloud microstructure.

Ice hazard as this long ago is already well known to pilots and designers, it appears in flight in the water clouds, which consist of the supercooled drops of water, or in the clouds which contain both the supercooled drops and ice crystals (mixed clouds). In flight in the clouds which consist only of ice crystals, icing, as a rule, does not occur.

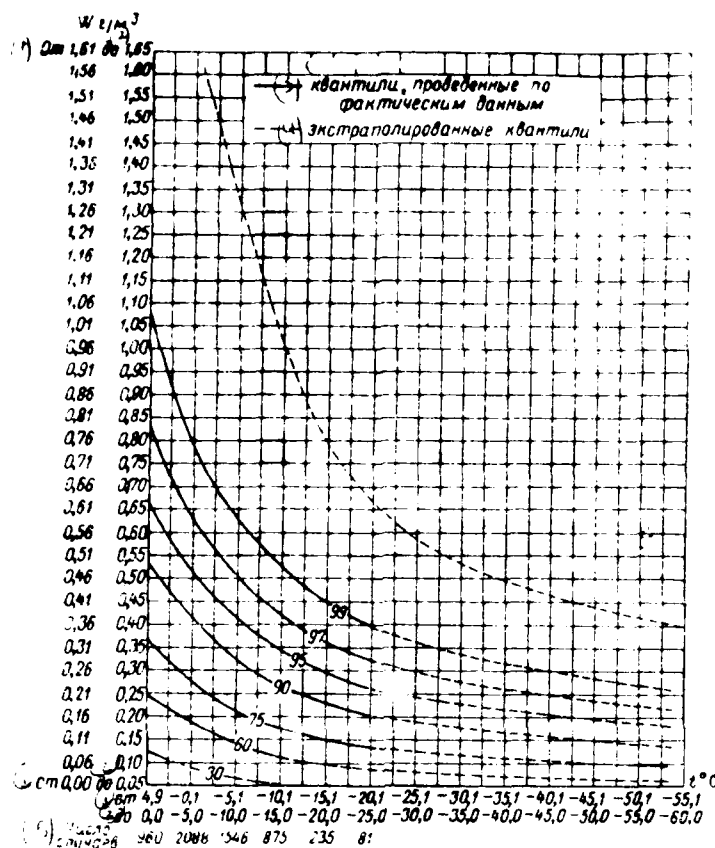


Fig. 2.2. Dependence of the quantiles of water content of clouds on the temperature of surrounding air.

Key: (1). From. (2). to. (3). quantiles, carried out according to actual data. (4). extrapolated quantiles. (5). Number of cases.

Actually/really, under normal conditions the ice crystals, encountering the cold surface of aircraft, slide down with it and are taken away by air flow. This does not mean at the same time that the ice crystals, which are contained in mixed clouds, play no role in ice formation on the surface of aircraft. For the author during experimental flights it was necessary in certain cases to observe as the solid freezing particles they sprinkled themselves into the film of ice, formed by the supercooled drops on surface the top or another aircraft component ¹.

FOOTNOTE this fact usually is not considered during calculations of deicers, or in different measurements of liquid-water content and icing intensity. ENDFOOTNOTE.

For evaluating that, how frequently with icing (and without icing) are encountered drop, crystal and mixed clouds, is brought table 2, constructed according to data of I. G. Pchelko.

As can be seen from table, on the average into 41o/o of observations the icing occurred in purely droplet clouds, into 54o/o - into those mixed and altogether only into 5o/o - in crystal ones. Depending on cloud forms the recurrence of water and mixed phases in clouds with icing changes. Water phase has the greatest recurrence in the stratus (St) and stratocumulus (Sc), altocumulus (Ac) clouds of

uniform air masses, and also in frontal nimbostratus and stratocumulus clouds (Ns-Sc). These clouds are characterized by the considerable probability of icing. The greatest recurrence of the mixed phase occurs in clouds Ns-As (nimbostratus, altostratus), characterized by comparatively small probability of icing, and in clouds Cb (cumulonimbus), for which the probability of icing is very great. The clouds, in which does not occur the icing, in the majority of the cases are mixed or crystal. In this case, as can be seen from table 2, the considerable number of observations without icing occurred also in purely water clouds (in average/mean 220/o).

several years ago during the flights of the transport aircraft through tropical areas was discovered phenomenon that of the called "dry" icing, i.e., icing in crystal clouds. This it forced to focus attention on the fact that under some conditions during the design of the systems, antiicing, it is necessary to consider the content of the crystals of ice in clouds. According to published communications/reports [25], [48] the complications in flight through crystal clouds were encountered in the tropical areas of Africa where occur the strong displacements/movements of air masses as a result of the great heating of the earth/ground. Up to now there is not even more precise information relative to the extent of such clouds, their liquid-water content, or sizes/dimensions of crystals. However, according to some data [25] the maximum concentration of ice is 6 g/m^3 , and the maximum size of crystals reaches 3 mm.

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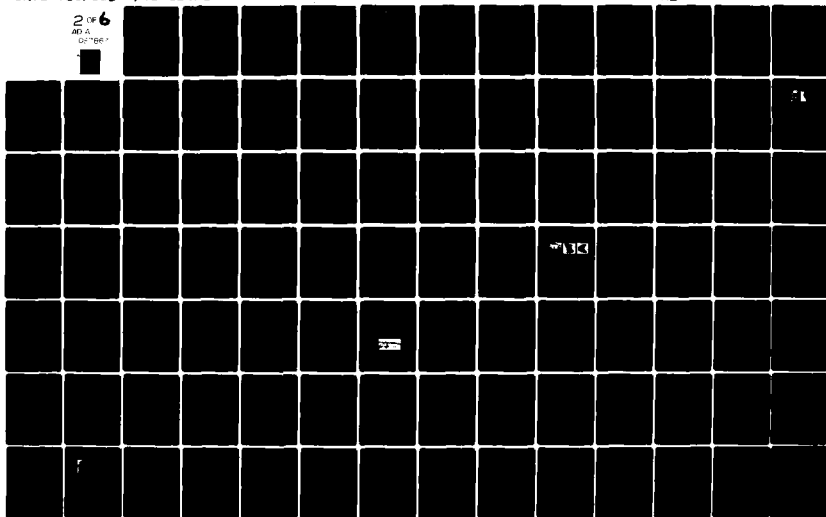
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Table 2. Recurrence of different phases of clouds.

(1) Форма облаков	(2) Число наблюдений при обледенении	(3) Повторяемость фаз облаков в %			(4) Число наблюдений без обледенения	(3) Повторяемость фаз облаков в %		
		(5) капельные	(6) кристаллические	(7) смешанные		(5) капельные	(6) кристаллические	(7) смешанные
(8) St, Sc и Ac однородных воздушных масс	710	74	2	24	138	68	10	22
(9) Ns-Sc-фронтальные	118	76	-	30	40	40	12	48
(9) Ns-Ac-фронтальные	246	12	8	80	254	2	20	78
(10) Ac-все случаи	182	30	12	58	131	2	18	50
(10) Cb-все случаи	100	18	3	79	70	-	41	59
(11) Средняя повторяемость %					-	(11) Средняя повторяемость %		
						22	26	52

Key: (1). Cloud form. (2). Number of observations with icing. (3). Recurrence of phases of clouds in o/o. (4). Number of observations without icing. (5). drop. (6). crystal. (7). mixed. (8). St, Sc and Ac of uniform air masses. (9). frontal. (10). all cases. (11). Average/mean recurrence.

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In this case the large part of the crystals (about 90%) has a size/dimension (diameter) less than 150 μ . The phenomenon of "dry" icing was discovered in flight through the apexes/vertexes of the cumulonimbus clouds, containing a large quantity of crystals of ice. The made observations show that the height/altitude, at which in essence in tropics are encountered the clouds, which contain a large quantity of crystals, oscillates from 6000 to 9000 m. The extent of ice clouds can reach several hundred kilometers.

Clouds with the crystals of ice are formed from those supercooled. If in cloud together with the supercooled drops are crystals, then their size/dimension they will increase, because the cloud, saturated with respect to supercooled water, will be oversaturated according to relation to ice (since the pressure of the saturating vapor above ice is considerably less than above water). In proportion to an increase in crystals due to sublimation on them of vapors the drops will evaporate for maintaining the saturation of air. This process will continue until entire cloud becomes purely crystal.

As noted in the majority of observations crystals they are not detained on the cold surface of aircraft. However, if its temperature

higher than 0°C (as a result of the work of anti-icing system, kinetic heating or other reasons), then crystals, coming into contact with surface, deposit on it, partially or completely they melt and they can anew freeze.

Another serious danger consists in the accumulation of crystals in the air intakes of engines, which can bring, as this was observed on aircraft "Britain", to the disruption of their work.

However, "dry" icing is rare phenomenon. Frequent and dangerous cases of aircraft icing are connected with the existence of the supercooled drops.

The value of cloud drops is different. It is known that the drops of rain can reach several millimeters in diameter. However, most frequently in clouds are encountered the drops whose diameter is $10-15\ \mu$. The clouds of small vertical power/thickness (laminar, stratocumulus, flat/plane cumulus) contain smaller in size drops than the nimbostratus, cumulonimbus and cumulus congestus clouds.

As showed observations, the majority of clouds of their upper part consist of more major drops, than of lower. Coarsening/consolidation of drops and increase in the liquid-water content with height/altitude causes an increase in the icing

intensity in the upper part of the cloud layers.

The size/dimension of drops plays large role in the formation/education of the form of ice outgrowth on wing profile.

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The study of the microstructure of droplet clouds, which was being carried out in TSAO under the management/manual of A. M. Brovikov, and also a number of foreign investigations (V. Lewis et al.) made it possible to obtain sufficiently vast material about the distribution of drops according to sizes/dimensions in the clouds of various forms. In Soviet works the size/dimension of drops in one or the other cloudiness is usually characterized arithmetic mean radius r_{ep} .

In the clouds of laminar forms r_{ep} usually it oscillates from 4 to 8 μ (in the majority of cases r_{ep} it does not exceed 5 μ). In the nimbostratus cloudiness or frontal zones r_{ep} it reaches sometimes 12-13 μ and more [2]. With a decrease in the temperature of air r_{ep} of drops it decreases.

It is characteristic that according to V. Lewis's data is observed the considerable difference in dimensions of the drops

between seaside areas and territories, distant from the ocean. In table 3, given below, borrowed from the monograph "physics of clouds" [1], it is shown that the mean radius of the drops of the clouds of various forms in the Pacific Ocean coast of the USA substantially exceeds r_{cp} drops in the clouds of continental areas.

Values r_{cp} , given in table 3, exceed the mean radii of drops, measured in the investigations by TSAO above the territory of the Soviet Union.

In foreign works on the problem of icing often is used the concept of the "mean effective diameter of drops" ($d_{ep,эф}$). This term means that in the drops whose diameter is more than average/mean effective, is contained as much water, as in drops with the diameter smaller than the average/mean effective.

Fig. 2.3 gives the graph/curve, which illustrates the frequency of the cases of icing at the different values of the mean effective diameter of drops $d_{ep,эф}$. Graph/curve is constructed according to data NACA [31]. As we see, into 950/0 of cases the mean effective diameter did not exceed 30 μ , but its maximum value attains 50 μ .

Fig. 2.4 shows change $d_{ep,эф}$ in heights/altitudes for stratus and cumulus clouds. Graph/curve is borrowed from work [38].

In contrast to liquid-water content the size/dimension of drops plays smaller role in the speed of the increase of ice. If depending on water content of clouds icing intensity can change 10 times, the change in the sizes/dimensions of drops (with permanent liquid-water content) can cause intensity change 3-5 times.

Table 3.

(1) Географический район	(2) Средний радиус капель облаков различных форм		
	<i>Al, Al-As</i>	<i>St, Sc</i>	<i>Cu, Cb</i>
(3) Тихоокеанское побережье США	9,4	9,9	9,8
(4) Другие районы США	7,1	5,4	8,8

Key: (1). Geographical area. (2). Average radius of drops of clouds of various forms. (3). Pacific Ocean coast of USA. (4). Other areas of USA.

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However, the size/dimension of drops has the high value with determination of the zone of ice accumulation on profile.

Taking into account the available data about dimensions of drops in the clouds of various forms, it is expedient in calculation to accept the mean radius of drops the equal to 8μ , which corresponds to an average/mean effective radius of 15μ ($r_{\text{eff}} = 1,83 r_{\text{cp}}$).

Extent of the zones of icing.

The resolution of the problem of flight safety under severe

weather conditions requires the value of the propagation of the zones of icing both on the vertical line and on horizontal.

These factors have high value both for the pilot and for a designer. For a pilot the knowledge of these zones makes it possible to determine possibility rate of icing and thereby its danger. For a designer the knowledge of the extent of the zone of icing is necessary because this determines the time of the determination of aircraft in the zone indicated and, therefore, the time of the continuous operation of de-icing system.

But it is not enough to have representation only about the possible and most probable propagation of icing. Are necessary data about the vertical and horizontal extent of the zones of the icing of different intensity and, in the first place, zones of heavy icing.

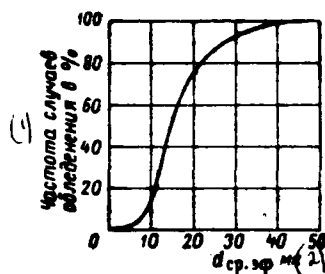


Fig. 2.3.

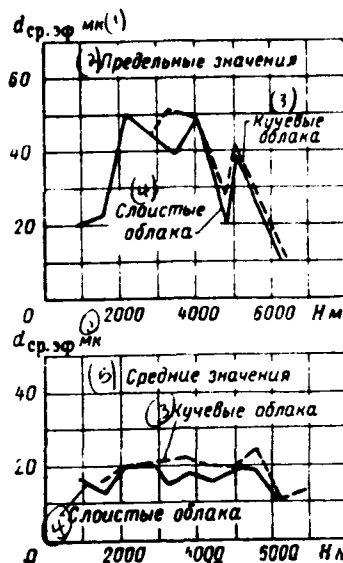


Fig. 2.4.

Fig. 2.3. Accumulated frequency of cases of icing for different values of average effective diameter of drops.

Key: (1). Frequency of the cases of icing in o/o. (2). μ .

Fig. 2.4. Values of mean effective diameter of drops for different heights/altitudes in stratified and cumuliiform clouds.

Key: (1). μ . (2). Limiting values. (3). Cumulus clouds. (4). Stratus. (5). Average/mean values.

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There is up to now very few published materials on this question. Conducted over a number of years in GosNII [State Scientific Research Institute] GVF experimental flights made it possible to obtain some data about the total length of the zones of icing; however, they were insufficient for differentiation of zones according to the degree of their intensity.

The great elongation/extent of the zones of icing in the horizontal plane is measured in hundreds of kilometers occurs in stratus and stratocumulus clouds. In this case the extent of zone decreases with an increase in the degree of water content of clouds, i.e., zones with intense icing are considerably less than zones with the icing of average/mean and weak intensity.

The regions of the icing of large intensity are encountered in cumulus clouds; however, the extent of separate cumulus cloud on horizontal rarely exceeds 20 km. It is necessary to consider that the aircraft can meet many such clouds during one flight.

The maximum extent of the zone of drop icing on vertical line occurs in cumuliform clouds and it reaches 3000-3500 m. It is necessary to keep in mind that the phenomenon of "dry" icing can introduce substantial changes into the numerals indicated toward their increase¹.

FOOTNOTE ¹. In chapter III in examination design conditions of icing are given official English data on the extent of the zones of the icing of different intensity (liquid-water content). However, these data, obviously, cannot be acknowledged by completely strict and cannot be common in all geographical areas. ENDFOOTNOTE.

2. Probability of icing up under different synoptical conditions.

The probability of the icing of high-speed/velocity and "slow" aircraft is different as a result of different effect on the icing of the kinetic heating of their construction/design. However, since the kinetic heating of construction/design can be determined in each specific case, it is expedient to examine the probability of aircraft icing only on the basis of different synoptical conditions without taking into account the flight speed, i.e., only in dependence on the characteristics of clouds themselves.

Aircraft icing in synoptical conditions most completely it was

different studied by Soviet researcher I. G. Pchelko. On the basis of data of sounding the atmosphere, that were being conducted on the aircraft LI-2, for which it is possible to virtually disregard the effect of kinetic heating, by it it was constructed with Table 4.

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From table it is evident that the greatest probability of aircraft icing falls to flights in uniform air masses.

For high-speed aircraft is observed the similar pattern, i.e., the majority of the cases of icing is connected with flights under conditions air-mass stratus and stratocumulus clouds, which is obviously explained by the predominantly drop structure of these clouds.

In clouds Ns-As (nimbostratus, altostratus) took the place of altogether only 17o/o of cases of icing.

Certain quantity of cases of icing (5o/o) was recorded in cirrus clouds at high altitudes, but, as this has already been noted, the microstructural special features/peculiarities of these clouds up to now still little studied.

I. G. Pchelko, analyzing statistical data on the icing jets in flights above the territory of the Soviet Union, arrived at the conclusion that in the cold season 60o/o cases of icing it falls to the heights/altitudes less than 3000 m.

Table 4. Quantity of cases (in o/o) with icing and without icing during flights on aircraft Li-2 and under different synoptical conditions.

(2) Число наблюдений (3160)	(1) Количество случаев в % при следующих синоптических условиях					
	(3) Однородные воздушные массы		(4) Фронтальные зоны			
	в холодном фронте (780 наблюдений)	в теплом фронте (750 наблюдений)	в теплом фронте (720 наблюдений)	в холодном фронте (570 наблюдений)	в размытом фронте (230 наблюдений)	в центре циклона (110 наблюдений)
(9)	(5)	(6)	(6)	(5)	(7)	(8)
2255 с обледенением	80	82	59	77	70	52
905 без обледенения	20	18	11	23	21	48

Key: (1). Quantity of cases into o/o under the following synoptical conditions. (2). Number of observations. (3). Uniform air masses. (4). Frontal zones. (5). in cold front (780 observations). (6). in by heat front (750 observations). (7). in diffuse front (230 observations). (8). in cyclone center (110 observations). (9). with icing. (10). without icing.

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The recurrence of icing at the heights/altitudes, which exceed 5000 m, sharply decreases. A quantity of cases of icing at height/altitude on the order of 8000 m composes only 7o/o¹.

FOOTNOTE 1. In work [16] is described the case of sublimation icing at heights/altitudes from 11000 to 5000 m, which was observed with a reduction in the aircraft from the height/altitude of 16000 m. It is characteristic that during the climb under the same conditions the icing did not occur. ENDFOOTNOTE.

These data it is interesting to compare with the results, obtained by the author during special flights on aircraft with TRD [turbojet engine] and TVD. Flights were conducted mainly with the purpose of the tests of the de-icing systems of aircraft. Working/treatment of 343 cases of icing allowed it will construct the graph/curve, given in Fig. 2.5, which shows the recurrence of icing on heights/altitudes for the central area of the European Territory of the USSR.

As it follows from graph/curve by 550/o of cases of icing it proceeded at heights/altitudes from 0 to 3000 m, and 880/o of cases - at heights/altitudes from 0 to 5000 m. These results are close to data, obtained of I. G. Pchelko. In the examination of the graph/curve, given in Fig. 2.5 one should consider that the recurrence of the icing on scheduled flights at high altitudes will be somewhat above since the experimental flights, on the basis of results of which is constructed the graph/curve, were conducted predominantly at heights/altitudes to 5000 m with purpose of the most

confident determination of the conditions of icing.

In the examination of synoptic situation, it is necessary for the pilot to focus attention on that, it will flight pass to internal clouds (in a homogeneous air mass) or with the intersection of the fronts (heterogeneous air masses connected with interaction), what in this case types of cloudiness can be encountered and at what height/altitude are found upper and lower cloud bases.

Some clouds, which were being formed as a result of different processes, according to their appearance are similar between themselves. This can lead to the incorrect estimation of the conditions of icing.

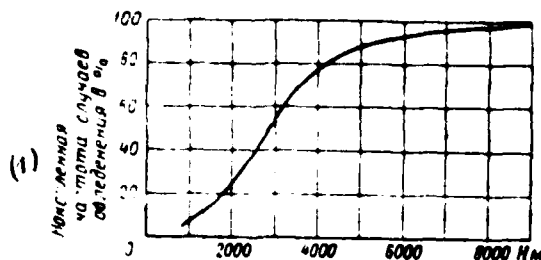


Fig. 2.5. Accumulated frequency of the cases of icing (343 cases) for different heights/altitudes (according to data of the experimental flights of aircraft with FMD and TVD).

Key: (1). Accumulated frequency of the cases of icing in o/o.

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For example, the cumulonimbus clouds and nimbostratus are characterized by the varied conditions of icing; however, frequently these cloud forms are mixed.

Among pilots, and also synoptics there is an opinion that the icing appears mainly during the intersection of fronts. Actually/really, according to the observations of the pilots of scheduled flights most frequently the icing occurs in frontal zones.

However, in this case it is necessary to bear in mind the following: frontal cloudiness is characterized by considerable vertical development, in consequence of which during the intersection of the front of clouds the pilot always cannot fly above clouds. The clouds of uniform air masses have on vertical line considerably smaller extent, which makes it possible for pilot to fly above them and, therefore, to avoid icing. Therefore the great number of communications/reports about icing falls to frontal cloudiness.

While conducting of special flights for the investigation of the conditions of icing it was established/installed, that the strong icing frequently can occur, also, in the clouds of uniform air masses. It is explained this by the fact that the zone of icing in the clouds of uniform air mass covers entire supercooled drop region of these clouds. Stratus and stratocumulus clouds can stretch to very large areas and the zone of icing in them can reach 1000 and more than kilometers. Therefore flight in such clouds can be prolonged and rate of icing will be considerable.

Table 5 gives on the basis of observations in experimental flights on the aircraft of Il-12 and Il-14 data about a quantity of cases of the icing of different degree.

Table 5. Quantity of cases of the aircraft icing of Il-12 and Il-14 in flight (on height/altitude to 4000 m) depending on synoptic situation.

(1) Синоптическая обстановка ¹	(2) Количество случаев обледенения в % при степени обледенения		
	(3) слабый	(4) средний	(5) сильный
Теплая однородная воздушная масса (6)	61	35	4
Холодная однородная воздушная масса (7)	55	27	18
Теплый фронт (8)	75	23	2
Холодный фронт (9)	76	21	3

Key: (1). Synoptic situation¹.

FOOTNOTE ¹. The determination of the scale of rate of icing is given on page 54. ENDFOOTNOTE.

(2). Quantity of cases of icing in o/o with rate of icing. (3). weak. (4). by average. (5). strong. (6). Warm uniform air mass. (7). Cold uniform air mass. (8). warm front. (9). Cold front.

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From this Table 5 it is evident that a great number of cases with strong icing was observed in cold uniform air masses.

This, of course, it does not mean that in frontal zones it cannot be encountered strong rate of icing.

It should be noted that this table, obtained on comparatively limited data and relating to heights/altitudes to 4000 m, he indicates only the possibility of strong aircraft icing and in the clouds of uniform air masses, which always is not considered in proper measure by pilot. However, the cases of especially strong icing, as a rule, were connected with frontal zones.

All clouds of uniform air masses (laminar, stratocumulus, cumulonimbus and cumulus) are characterized by the fact that in their upper part they have more major drops and large liquid-water content, that also causes more intense icing in this part of the cloudiness. Especially intense icing can be in the cumulonimbus clouds. On the contrary, nimbostratus and altostratus cloudiness of warm fronts is frequently characterized by the high sizes/dimensions of drops and by the high values of liquid-water content in its lower part where consequently, and is observed the most intense icing.

With intense snowfall the cloudiness of warm fronts is impoverished of drop moisture. Therefore sharply pronounced warm

fronts with powerful/thick vertical cloudiness and heavy precipitation in the form of snow are not usually accompanied by strong icing. The icing of large intensity is possible in warm-front clouds when they do not have too considerable a vertical development and do not give considerable precipitation in the form of snow. This makes it necessary to reexamine the opinion propagated until this time among pilots that the zones of intense icing in by heat front coincide with its those sections where falls heavy precipitation in the form of snow. The horizontal extent of the zone of icing during the intersection of warm front (in perpendicular direction) can reach 200-400 km.

The vertical extent of the zone of icing in warm-front clouds is limited to the height/altitude of the transition of droplet clouds into crystal or mixed clouds and can reach 2000-2500 m and more.

Icing in cumulonimbus cold-front clouds bears identical character with icing in the cumulonimbus clouds of uniform air masses, since the fundamental difference in structure not no those and other clouds there are. Icing intensity in the cumulonimbus clouds in their upper part can reach very high values.

3. Degree and icing intensity.

Should be distinguished rate of icing, under which is understood a quantity of ice, which was being formed on aircraft for the time of entire flight under conditions of icing, from icing intensity, i.e., from the speed of build-up/growth or ice formation. Both these concepts is closely related to each other.

Rate of icing is determined by the rate of formation of ice and by the retention time of aircraft under conditions of icing. For example, if aircraft short-term was found under conditions of intense icing, rate of icing, i.e., a quantity of ice, which was plotted on the surface of aircraft, can be small. ^A And, on the contrary, in other case with the execution of flight in the zone, which is characterized by weak icing intensity, on aircraft can be formed a large quantity of ice due to its prolonged stay under conditions of this zone. Thus, icing intensity yet does not determine the quantity of ice, which is accumulated on the external surface of aircraft.

The surfaces of separate aircraft components in dissimilar measure are subjected to the icing; a quantity and the thickness of ice forming on them are different. It is obvious that for the characteristic of rate of icing it is necessary to agree, with respect to what aircraft component it is established/installed.

FOOTNOTE 1. In the literature however frequently are given the quantitative values of intensity and rate of icing without the indication of concrete/specific/actual aircraft component. In the majority of such cases it is implied that the discussion deals with ice formation on wing. ENDFOOTNOTE.

The used concepts: "slight icing", "moderated", "strong", under which more frequently is understood rate of icing, must, obviously, express to what extent dangerous these or other the conditions of icing for this aircraft. Different aircraft types are differently equipped by anti-icing means. Furthermore, the effect of icing on aircraft performance can sharply change with the same thickness of ice outgrowth in dependence on its form.

Therefore, in order to determine how dangerous is icing, it is necessary to know: the effectiveness of the anti-icing protection of this aircraft, the intensity of the increase of ice, the temperature of surrounding air, the extent of the zone of icing and finally the form of the generatrix of ice. Because of this to give the concrete/specific/actual scale the degree or icing intensity for all aircraft types is difficult and such concepts as "weak", "moderate" or "strong" icing, they bear in practice faster qualitative, than

quantitative character.

For determining the icing intensity are applied the special instruments, based on different principles. In this case the icing intensity frequently measure not by the mass of deposited ice, but according to change the thicknesses of ice layer per unit time.

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On aircraft for sounding, and also in the series/row of scheduled flights (for example, 11-14, 11-18) sometimes is utilized for this purpose the indicator of icing, which is the small profile with measuring rod, with the aid of which the pilot can determine thickness and speed of the increase of ice, forming on indicator. This method, in spite of its low accuracy and number of other deficiencies/lacks, has the advantage that besides the icing intensity and thickness of ice the pilot can also determine the form of icing, which has important value for the evaluation of the effect of icing on flight aircraft quality/fineness ratios.

Fig. 2.6 gives the photograph of the standard indicator applied in test flights of the icing GosNII GVP, which is equipped with electric heating for the periodic removal/distance of ice. In connection with this type of indicator in Table 5 is conditionally

accepted the following scale of rate of icing:

- weak icing - thickness of ice on indicator of less than 15 mm;
- average/mean icing - thickness of ice on indicator from 15 to 30 mm;
- strong icing - the thickness of ice on indicator is more than 30 mm.

While conducting of the tests of de-icing system it must be determined are the condition of the natural icing which encompass the temperature of surrounding air, liquid-water content, size/dimension of drops, duration of icing. Liquid-water content and size/dimension of drops can be united for the definite flight speed in one parameter - icing intensity which depending on the coefficient of settling drops is different for the bodies of various forms, and which determines change per unit time of mass or thickness of the generatrix of ice.



Fig. 2.6. standard sight indicator of icing GosNII GVF Il-18 installed on aircraft.

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Is obvious, precisely, a quantity of ice forming per unit time together with the temperature of surrounding air and by time factor it will determine, to what extent are light or severe conditions of the icing, in which tests the de-icing system. The icing intensity of standard indicator is determined by the following formula: ¹

$$J_{\text{VK}} = \frac{\beta E_{\text{exp}} V W}{60 q_1} \quad (2.1)$$

where J_{VK} - an icing intensity of indicator in the mm/min;

β - dimensionless coefficient of freezing,

$\tilde{E}_{\text{f.sp.}}$ - a dimensionless integral local coefficient of falling of the drops;

V_0 - true airspeed of aircraft in the km/h;

W - water content of clouds in g/m³;

ρ_i - density of the generatrix of ice in g/cm³.

FOOTNOTE 1. It is not difficult to see that formula (2.1) is obtained from formula (1.1), in contrast to which the icing intensity is expressed here in mm per minute. ENDFOOTNOTE.

The geometric dimensions of standard indicator are selected in such a way that the coefficient of settling drops E depending on a possible change in the sizes/dimensions of drops and flight speeds changes within small limits and can be accepted equal to 0.9. The coefficient of freezing β , which is the ratio of the mass of the generatrix of ice to the mass of the depositing water, as show calculations [12] at temperatures of air below minus of 5°C in the majority of the cases changes insignificantly and is close to unity for the specific speed range. With especially large water content of clouds and large flight speed the coefficient β can considerably differ from unity.

Ice density can change substantially; however, its effect on the icing intensity of indicator is incomparably weaker than water content of clouds whose values can change ten times.

For the exception/elimination of the direct effect of flight speed it is possible to introduce the relation:

$$\tilde{J} = \frac{J_{yk}}{V_{\infty}} \quad (2.2)$$

where \tilde{J} - the relative intensity (in mm/km), which characterizes the thickness of ice, the patas forming on the standard indicator with the passage of unity;

J_{yk} - speed of the increase of ice on standard indicator the mm/min;

V_{∞} - true airspeed of aircraft in km/min.

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Thus, the parameters of medium at the tests of the anti-icing system can be approximately evaluated by path from the measurement of the temperature of surrounding air, relative icing intensity and its

duration.

Processing static data for period from 1954 through 1962, obtained GosNII GVF during the tests of aircraft under conditions of natural icing they made it possible to establish/install the recurrence of relative icing intensity at different temperatures of surrounding air. Were processed 887 cases of the icing whose duration comprised not less than 5 minutes¹.

FOOTNOTE ¹. In working/treatment and analysis of material accepted lots the engineers V. V. Pazylov and A. A. Vodyanaya. ENDFOOTNOTE.

The assembled material was obtained in essence on aircraft with TRD and TVD and partially on piston-engined aircraft.

Fig. 2.7 gives the isopleths of the recurrence of the relative icing intensity of standard indicator in percentages of a total quantity of cases (887) depending on the values of the temperature of surrounding air. Data are related to the conditions of icing above the territory of the European USSR in autumnal, winter and spring periods and cover altitude range to 8500 m. As can be seen from graph/curve, relative intensity, reaching with temperatures from -5 to -10°C high values (on the order of 1-1.5 mm/km), sharply decreases at temperatures lower than -15°C, and, for example, for the isopleth,

which corresponds to 10/0 or cases, it is within the limits of 0.11-0.15 mm/km for a temperature range from -20.1 to -25°C.

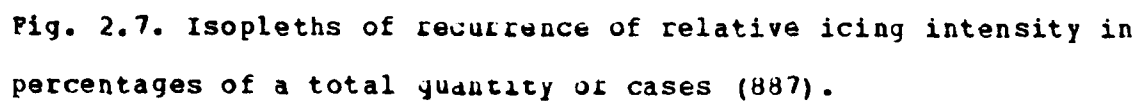
It should be noted that the character of curves on graph/curve shows that the icing can occur at very low temperatures of surrounding air, apparently, up to -50 - -60°C, that also is confirmed by actual observations in cumulonimbus clouds.

Three points (A, B, C) separately plotted/applied on graph/curve, correspond to three actually observed cases of icing under severe conditions. Moreover point B is related to the case of intense icing at temperature from -44 to -46°C, which occurred at the height/altitude of 8540 m in flight of the aircraft of Il-18 above Atlantic in section Keflavik-Gallirak on 5 October, 1961.

The duration of icing was about 15 min.

The comparison of this graph/curve with the analogous ones, which relate to water content of clouds (see Fig. 2.1), shows that the character of curves is close in both cases. However, it is possible to assume that data on liquid-water content in the range of temperatures from 0 to -10°C are somewhat understated in comparison with the actually observed values of icing intensity.

Another graph/curve (Fig. 2.8) illustrates the dependence of the quantiles of the relative icing intensity of different percentage on the temperature of surrounding air. For example, upper curved graph/curve is 990/o quantile which shows that 990/o of cases for each temperature range of the external of air the observed values of relative intensity were less than the values, corresponding to this curve. So, at temperatures of surrounding air from -25 to -30°C in 990/o of cases of the value of relative intensity they did not exceed 0.2 mm/km.



Key: (1). from. (2). to. (3). isopleths, carried out according to

actual data. (4). extrapolated isopleths.

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Without submerging to the detailed analysis of the led graphs/curves, let us note that they for the first time establish connection/communication between the directly measured icing intensity and by the temperature of surrounding air and they make it possible to propose the standard conditions under which must be checked the de-icing system of aircraft. Graphs/curves at the same time show that if we are oriented to the maximum values of relative intensity, natural condition test of icing they will require a very large quantity of flights, taking into account small probability of encountering the required conditions.

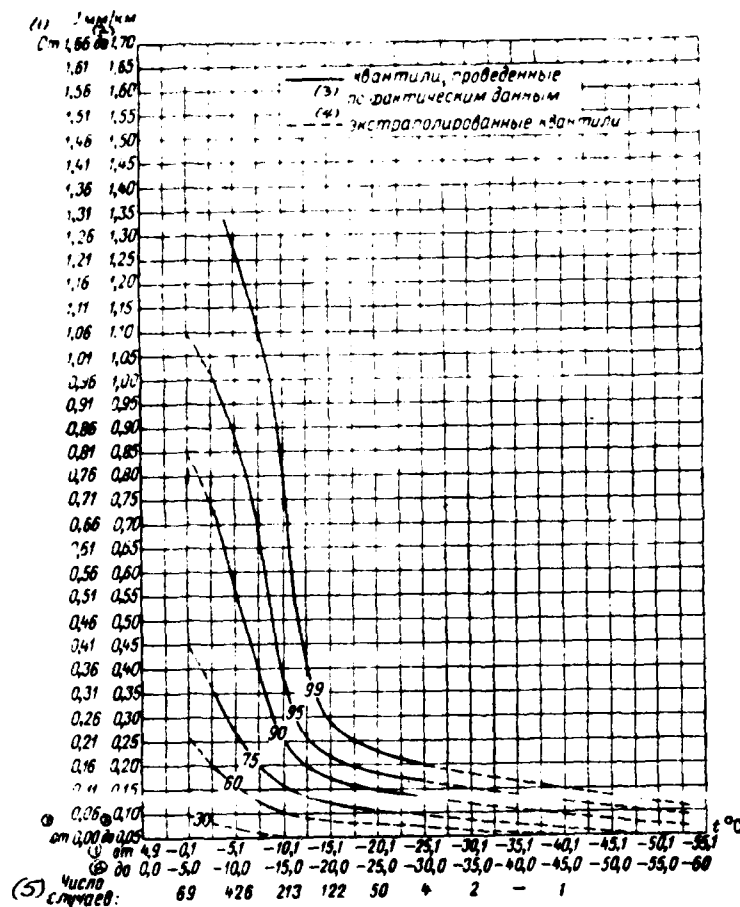


Fig. 2.8. Dependence of the quantiles of relative icing intensity on the temperature of surrounding air.

Key: (1). from. (2). to. (3). quantiles, carried out according to actual data. (4). extrapolated quantiles. (5). Number of cases.

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One should also bear in mind that in spite of a considerable number of cases (887), this material it is related to the specific geographical area and to the specific period of time and therefore it cannot pretend to the comprehensive completeness.

Is of practical interest the establishment of the dependence between the icing intensity of indicator and wing of aircraft.

For this purpose with the execution of experimental flights on the aircraft of Il-14 were conducted the simultaneous measurements of the thickness of ice on standard indicator and it is direct on leading wing edge in the section, thickness ratio in which composed ~150/o, and chord length 3.1 m [17]. As a result was obtained the graph/curve, given in Fig. 2.9. Measurements were conducted in 12 flights. The form of ice in each flight sharply was changed. that the obtained dependence between the icing intensity of indicator and wing is valid for the majority of the conditions of icing. We will compare the obtained experimental data with theoretical ones.

The icing intensity of wing $J_{кр}$ is expressed by the following formula:

$$J_{кр} = 3 \frac{\tilde{E}_{л.кр.точ.и.крыла} \cdot V_{\infty} \cdot W}{6000} \quad (1) \quad (2.3)$$

мм, мин.

Key: (1). mm/min.

where $\tilde{E}_{\text{крит. точки крыла}}$ - dimensionless integral local coefficient of settling near the critical point of wing profile.

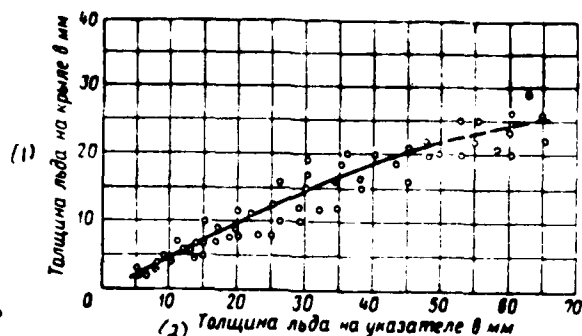


Fig. 2.9. Dependence between the icing intensity of wing and standard indicator.

Key: (1). Thickness of ice on wing in mm. (2). Thickness of ice on indicator in mm.

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Fig. 2.10 gives theoretical dependence $E_{\text{л.кр.точки крыла}}$ and $E_{\text{л.кр.точки указателя}}$ on the mean radius of drops $r_{\text{ср}}$ for speed 270 km/h. If we disregard/neglect changes in the coefficient of freezing for the wing and the indicator, which undergo icing under identical conditions, then will be valid the relation:

$$\frac{J_{\text{кр}}}{J_{\text{у}}} = \frac{E_{\text{л.кр.точки крыла}}}{E_{\text{л.кр.точки указателя}}}$$

accepting $r_{\text{ср}} = 5 \mu$ (as the most frequently encountered

size/dimension of drops) and using graph/curve in Fig. 2.10, we will obtain

$$\frac{J_{kp}}{J_{\text{sk}}} = 0.52.$$

Let us turn again to Fig. 2.9, from which it is evident that until ice outgrowth substantially distorts form and geometric dimensions of indicator, the relation to the icing intensity of wing to the icing intensity of indicator does not exceed the limits of 0.46-0.48. This testifies about the satisfactory convergence of experimental data with theoretical ones. Certain scatter of points on graph/curve is explained mainly by oscillations/vibrations in value r_{cp} , and also by errors of observation.

With large thicknesses of ice the given dependence between the icing intensity of wing and indicator no longer follows theory, since wing profile and profile of indicator cease to be by the easily streamlined bodies, and calculations to them in this case are not applied. An insufficient quantity of points and their considerable scatter does not make it possible to confidently conduct curve $J_{up}=f(J_{\text{sk}})$ with the thickness of ice of more than 60 mm.

In experimental flights besides visual observations of the increase of ice on wing and standard indicator was conducted continuous recording (tape recording) of the icing intensity of a

rotating cylinder, which was the receiving part of the special instrument - the aircraft meter of icing (SIO). The speed of the increase of ice for the rotating round cylinder is expressed as follows:

$$J_u = \frac{\tilde{E}_u \cdot V_{\infty} \cdot W}{60\pi \rho_a} \quad (2.4)$$

where J_u - an icing intensity of cylinder the mm/min;

\tilde{E}_u - integral complete coefficient of settling.

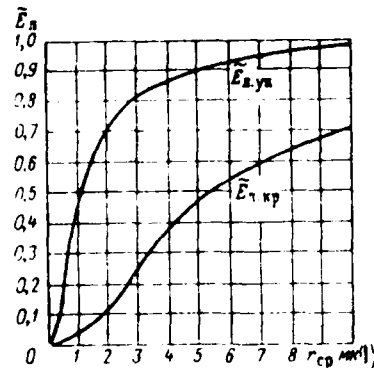


Fig. 2.10. Dependence of the integral local coefficients of settling for a wing and an indicator on the mean radius of drops.

Key: (1). μ .

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Simultaneous measurement in the flights of values I_0 , W and sizes/dimensions of drops (that made it possible to calculate the coefficient of settling E_n) it came to light/detected/exposed the conformity of findings with theoretical ones, and also the satisfactoriness of the applied methods for measuring of liquid-water content and cloud microstructure. Certain disagreement of the measured icing intensity of cylinder with that calculated should be related mainly due to the assumption of the permanent density of ice.

In the literature is given the most varied information about a maximally possible icing intensity. Frequently in old prewar sources it is possible to meet the numeral of 25 mm/min, true, given without the indication of that, to what aircraft component it is related.

In order to determine, which in actuality possible maximum icing intensity, let us turn anew to data about the liquid-water content of supercooled clouds and let us produce the calculation of the rate of formation of ice according to formula (2.3). In this case, taking into account that with large liquid-water content and insufficient to the low temperature of air freeze will all depositing on profile water (coefficient of freezing $\mu < 1$), let us explain the maximum values of water content of clouds at temperature of air below minus of 15°C .

From graph/curve in Fig. 2.2 it is evident that at the temperature indicated in 990/0 of cases the liquid-water content does not exceed 0.5 g/m^3 . However, this does not eliminate the much larger values of water content of clouds. In all known to the author measurements (discussion deals with direct measurements with the aid of instruments), water content of clouds at temperatures of air of lower than -15°C did not exceed 2 g/m^3 (this value is not by the

"instantaneous", but average for a period into several minutes).

Let us determine the icing intensity of the wing of aircraft, which flies with true airspeed 600 km/h. The integral coefficient of settling drops near the critical point of wing profile with chord 3-5 m can be accepted, as this follows from graph/curve in Fig. 1.16 equal to 0.7. Water content of clouds let us accept 2 g/m³ and densities of ice 0.8 g/cm³.

Then

$$J_{\text{кр}} \approx \frac{0,7 \cdot 600 \cdot 2}{60 \cdot 0,8} = 17,5 \text{ мм/мин.}^{(1)}$$

Key: (1). мм/мин.

As we see the obtained result so already it is not distant from the numeral of 25 мм/мин, given in prewar literature. One should, true, note that the coefficient of freezing β for given speed and liquid-water content will be at temperature of -15°C substantial less than unity which will lower the value of intensity.

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The given elementary calculation is shown, how high a rates of formation of ice can be encountered in nature¹.

FOOTNOTE 1. For the author in numerous experimental flights it was repeatedly necessary to fix/record the intensity of icing (on standard index) on the order of 2-3 mm/min, and only twice it was possible to observe in cumulonimbus cloudiness the intensity which was 6-7 mm/min, that was evaluated as especially severe conditions of icing. However, in the case with aircraft "Vanguard", to which already they referred and which is described at the end of this chapter the icing intensity of wing it reached, apparently, not less than 25 mm/min. ENDFOOTNOTE.

4. Forms of icing.

Up to now is absent the conventional classification of the forms of icing. The difficulties of development by clear, simple, and at the same time sufficient precise and detailed classification will become clear, if we remember entire diversity of the factors on which depends the formation/education of one or the other form of ice.

Was proposed several different classifications, but they in majority their either are too complicated for practical targets or they were based on any sign/criterion and do not cover all characteristic features of one or the other form of icing. The forms

of icing should be distinguished by the conditions for their formation/education, the form of ice and by its distribution on the wing profile of aircraft.

The observations, made by the author with the execution of numerous flights under conditions of icing on different aircraft types, made it possible to establish/install [21] that different forms of the icing encountered in practice can be brought to the following two bases whose emergence is connected with the presence in the atmosphere of the supercooled water drops.

The icing of the first form is formed in the medium, which contains the sufficiently major supercooled drops. This the form of ice they call sometimes "pure/clean", "glassy", and also "transparent", which is not entirely accurate, since more frequently is formed semitransparent ice. By the characteristic feature of this form of icing is the considerable propagation of ice crust along the airfoil chord of the wing or aircraft, i.e., the large width of capture ice of profile. In this case directly on quite leading edge is formed the uneven ice outgrowth, in form which reminds the flat trough whose edge they are directed at certain angle toward the incident airflow (Fig. 2.11). In the sections of profile, distant from leading edge, appears the thinner layer of rough, uneven ice, that is spread at a distance of 200-300 mm and more along chord.

Ice accumulation on large width and emergence of U-shaped" ice outgrowth can be explained as follows.

As was shown, major drops are little deflected/diverted by the airflow which flows around about the body and because of this deposit on larger in width the section of surface, than small/fine drops. However, besides in addition to this large role it plays the spreading of drops on body surface. The process of the freezing of major drops is accompanied by the liberation of a considerable quantity of latent heat of fusion. If in this case the temperature of air too not low and heat exchange with the environment occurs then not rapidly, drops will freeze not immediately. Deposited on the wing surface, major drop under the action of airflow before freezing will spread on certain surface. However, small/fine drop is displaced insignificantly, and it freezes almost instantly. The spreading of major drops and their freezing at certain distance from leading edge it will cause with the execution of the flight of aircraft in the medium where predominate major drops, more intense increase of ice on the edges of profile, that also will lead to the emergence of characteristic "U-shaped" ice outgrowth.

Sometimes is explained the formation/education of this form of

ice outgrowth by the effect of the kinetic heating of the wing surface and by the positive temperature in the zone of its leading edge. In this case of drop (large/coarse and small/fine) they will flow on upper and over pressure side of profile into the sections of wing more distant from leading edge with minus temperature, on which will occur their freezing. However, this does not explain the emergence of the "U-shaped" form of ice in flight at speeds 200-300 km/h, when heating the wing surface virtually can be disregarded/neglected (with sufficiently low temperature of surrounding air).

Color and specific weight of ice is determined by the conditions for its formation/education. The spreading of drops it leads to the fact that with freezing between separate drops barely remains air bubbles. Because of this is formed dense semitransparent ice, which possesses the greatest cohesive force with the surface of aircraft. The specific weight of this ice - 0.6-0.9 g/cm³.

Thus the formation/education of the first form of icing must occur with the specific relationship of the temperature of the external air and temperature of the surface of aircraft and with predominance in air of the sufficiently major supercooled drops (practice confirms this). The described form of icing most strongly affects a change in the aerodynamic characteristics of aircraft.

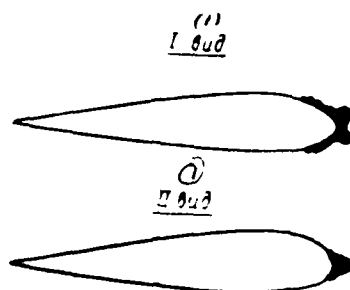


Fig. 2.11. Schematic diagram of two basic forms of icing.

Key: (1). form.

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The icing of the second form appears in flight in the clouds, which contain the small/fine supercooled drops, or the mixture of small/fine drops and ice crystals. This form of icing is called sometimes "mixed", and also "opaque" or "dull", which is not also entirely accurate, since its color can be different.

The form of icing indicated is formed in entire temperature range of icing and sufficiently solidly it floats of aircraft. Sometimes in this case icing has outwardly well expressed crystalline structure and then it is called "rime" or "crystal" ice. (One ought

not to forget that the internal structure of ice on all forms of icing is always crystal, and, if speak "amorphous" ice or "crystal", then in this case they bear in mind only its appearance).

The characteristic feature of the second form of icing is ice accumulation in a comparatively narrow section of the wing leading edge, near its leading edge. In this case ice outgrowth in the majority of the cases at first has tapered form. Opacity and considerably smaller specific weight of ice ($0.2-0.6 \text{ g/cm}^3$) are explained by the fact that the small/fine drops rapidly freeze, barely spreading over the wing surface, retaining the form of balls/spheres, in consequence of which this form of icing contains many smallest air bubbles. The presence in cloud of the ice crystals, which fall to the wing surface together with the supercooled drops, contributes to the almost instantaneous freezing of the latter.

From those examined or two evidently icing the first form is large danger for an aircraft. Is encountered it less often than a second. Frequently occurs intermediate type icing, which approaches either the first or the second form.

In special flights on the aircraft of Il-14 (total number of observations - 93) the icing of the first form appeared into 12.90/o of cases, second form - into 54.80/o and intermediate type icing -

into 32.30/o. According to the statistical data about the icing jets, obtained from crews, ice of the first form is encountered approximately into 300/o of cases.

Besides two forms of "arop" icing, known also icing in the form of hoarfrost, i.e., the light finely crystalline coating, which appears as a result of water vapor sublimation. The formation/education of hoarfrost on surface in flight is usually insignificant according to its sizes/dimensions. But it is necessary to remember that the hoarfrost, which was being formed on the surface of aircraft during its standing on the earth/ground is serious danger. If we the deposit of hoarfrost do not remove from the surface before the takeoff, then they can lead to serious consequences in flight.

Fig. 2.11-2.14 gives diagrammatic representations of two basic forms of icing, and also photographing of ice outgrowths.

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Fig 2.12



Fig 2.13.

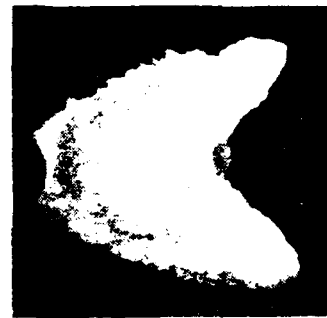


Fig 2.14

Fig. 2.12. Ice accumulation, close to first form of icing on sight indicator, established/installed on aircraft of Il-12.

Fig. 2.13. Ice outgrowth, split off from wing leading edge.

Fig. 2.14. Ice outgrowth, split off from thin profile (icing of first form).

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5. Short descriptions of separate flights under conditions of icing.

Is of practical interest the description of several examples of aircraft icing which was observed in experimental ones, and also in

usual, scheduled flights.

Example 1. 17 April 1958 aircraft Tr-104 during the execution of experimental flight in area g. Novosibirsk it met the icing of large intensity. The target of flight consisted in testing of the de-icing system of aircraft. Synoptic situation is represented in Fig. 2.15. Flight was conducted in cumulonimbus cloudiness of secondary cold front at the height/altitude of 1800 m at temperature of surrounding air from -5 to -6°C. The speed of aircraft according to instrument was 400 km/h.

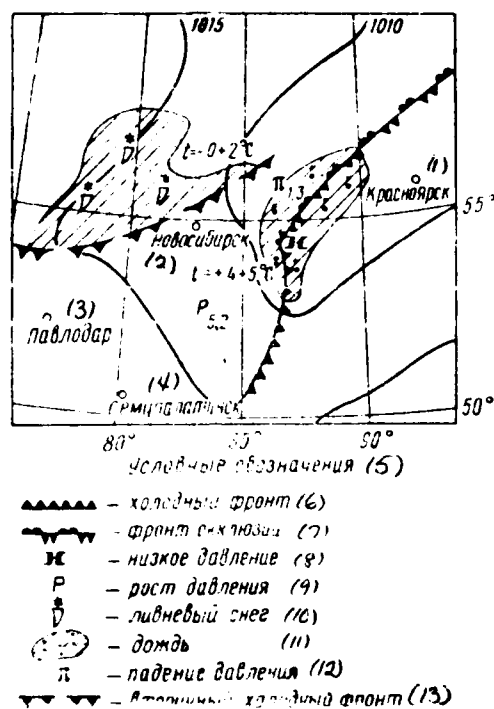


Fig. 2.15. Synoptic of situation in 15 hours on 17 April, 1958.

Key: (1). Krasnoyarsk. (2). Novosibirsk. (3). Pavlodar. (4). Semipalatinsk. (5). Conventional designations. (6). Cold front. (7). occluded front. (8). low pressure. (9). increase in pressure. (10). snow shower. (11). rain. (12). pressure drop. (13). Secondary cold front.

For a while in the beginning of flight icing intensity on standard indicator oscillated in the limits of 1.5-2.5 mm/min, but then sharply increased and it achieved 6 mm/min (for three minutes the thickness of ice on indicator increased by 18 mm). Under these conditions on unheated aircraft components was observed the rapid increase of ice. On the leading edges of wing and tail units in the connected de-icing system ice was not formed. At the same time as a result of the runoff of the drops of moisture from entering edge on profile on it beyond the limit of the warmed zone was formed so-called "barrier ice". For outcrop from the zone of icing the speed was increased to 650 km/h. At this speed ice descended with all aircraft components during 2 min.

Example 2. The same aircraft of Tu-104 on 21 April, 1958, with the execution of experimental flight, intersecting occluded front (Fig. 2.16), met icing in intensity more than 7 mm/min. In the zone of occluded front it was observed the development of cumulonimbus cloudiness and cloudbursts with thunderstorms.

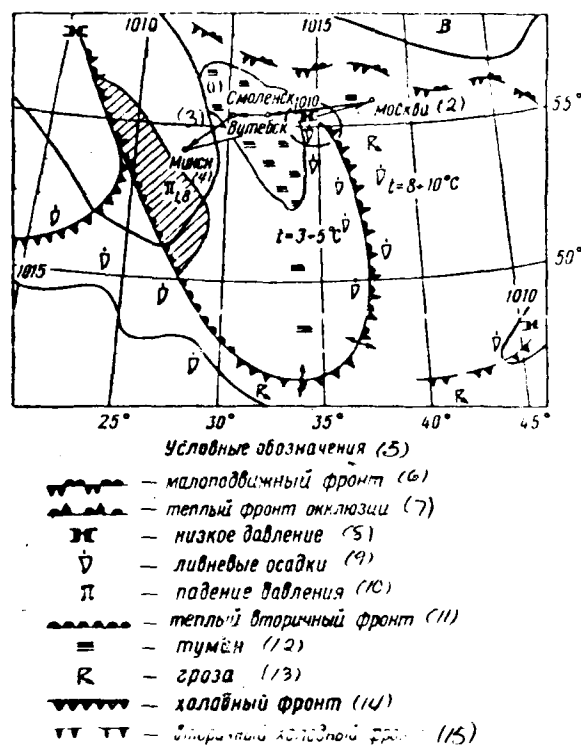


Fig. 2.16. Synoptic situation in 15 hours on 21 April, 1958.

Key: (1). Smolensk. (2). Moscow. (3). Vitebsk. (4). Minsk. (5).

Conventional designations. (6). Low-movement front. (7). warm

occluded front. (8). low pressure. (9). shower precipitation. (10). incidence/drop in pressure. (11)/ warm secondary front. (12). fog/mist. (13). thunderstorm. (14). cold front. (15). secondary cold front.

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To west from Minsk was arranged/located the section of warm front and the low-pressure trough connected with it which caused cloudy weather with widespread rain.

The contrast of the temperature of air masses, divided by occluded front, composed 5°C on 500 m, 3°C - on 1500 m, but at higher levels, it is more than 3000 m, occluded front in temperature field it was not outlined.

The zero isotherm was arranged/located, approximately/exemplarily, between 500 and 1000 m, but at the height/altitude of 3000 m the temperature of air reached from -9 to -11°C ; therefore at heights/altitudes from 500 to 3000 m in the layer of cloudiness of this front it was possible to expect intense icing and bumping of aircraft.

Flight was conducted at the heights/altitudes of 2000-2400 m,

with indicated airspeed 400 km/h, at temperature of surrounding air from -8 to -11°C with constantly connected deicer of aircraft and engine.

At first icing intensity in the average was 2 mm/min, in this case the aircraft periodically entered into cloudiness and left it. Under these conditions was observed the flowing in of moisture and ice formation in the unheated sections of keel and stabilizer, and also on the external surface of the air intakes of engines. Ice was formed also on the nose/leading edge of the air intake left-side engine which did not have the intensive heating. Wing remained free from ice.

After 10 min of flight in the cumulonimbus cloudiness the icing intensity sharply rose. After 3 min of flight the thickness of ice on indicator increased by 22 mm, i.e., icing intensity for this time interval achieved 7.3 mm/min. The temperature of surrounding air composed -11°C . Flight speed was increased to 600 km/h according to instrument; however, ice on some surfaces of aircraft remained up to outcrop from the zone of icing. Further with the set of aircraft altitude left the cloudiness, after which ice was distant from all aircraft components and engine.

After fitting/landing with inspection were discovered the

considerable damages of two blades of input guide ring and four blades of the first compressor stage on the engine which was not equipped by the improved de-icing system. These damages were the consequence of the incidence/impingement of ice into engine¹.

FOOTNOTE ¹. On the basis of the results of these tests the de-icing system of power plants was improved on all aircraft of Tu-104.

ENDFOOTNOTE.

Example 3. On 24 April, 1960, was conducted experimental flight on the aircraft of An-10 in area, situated on 200-300 km more northeastern than the Permian period. Flying area was located on the periphery of vast cyclone near the occluded front (according to the type of warm front), which divided the masses of more warm and colder continental air (Fig. 2.17).

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In warm air mass was observed altocumulus and featherlike cloudiness, in cold - stratocumulus and rain, in places fell snow. Fall under conditions of icing, in essence, it was carried out in the third (of four levels) from the earth's surface cloud layer. The clouds were optically dense, but their structure was mixed, in them snow fell. The power/thickness of clouds on all four levels was small, as a

rule, it did not exceed 200 m. Icing intensity oscillated from 0 to 1.6 mm/min.

Fig. 2.18 gives the graph/curve of a change in the icing intensity J and thickness of ice L in the standard indicator of icing, used in test flights in GosNII GVF (see Fig. 2.6). The thickness of ice on indicator is measured with the aid of dowel with divisions, and icing intensity is calculated as the increase in the thickness of ice, in reference to time ($\Delta L/\Delta t$ mm/min) corresponding to gap/interval.

Aircraft entered into the zone of icing at the height/altitude of 3500 m with the switched off deicers of wing and tail assembly. The temperature of surrounding air composed minus of 8°C ; indicated airspeed - 450 km/h.

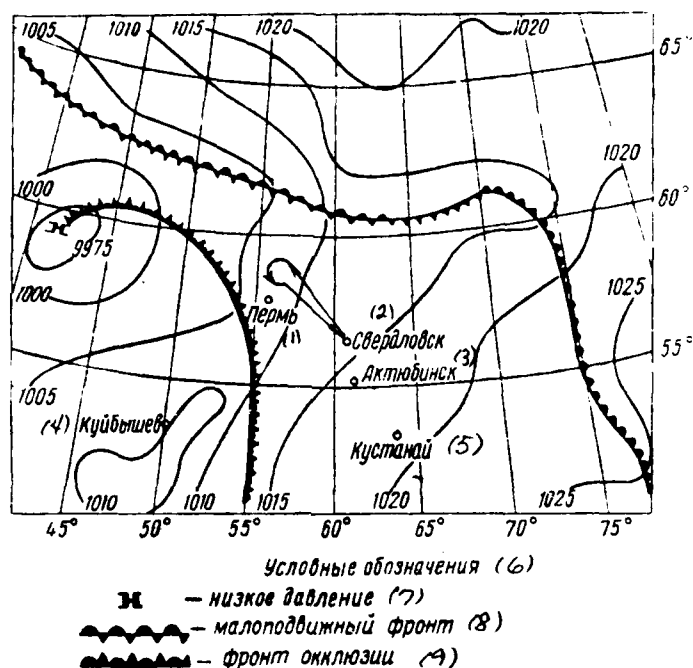


Fig. 2.17. Synoptic situation on 24 April, 1960.

Key: (1). Permian period. (2). Sverdlovsk. (3). It is Aktyubinsk. (4). Kuybyshev. (5). Kustanay. (6). Conventional designations. (7). low pressure. (8). low-mobility front. (9). occluded front.

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It is characteristic that in this flight were formed ice, close to the first form (semitransparent uneven with the large width of

deposit along profile - Fig. 2.19). This immediately affected a decrease in the velocity of level flight. With the thickness of ice on indicator of approximately 20 mm indicated airspeed (during the constant/invariable mode of operation of engines) fell by approximately 40 km/h.

Example 4. In flight on 25 April, 1960, the aircraft of An-10 met the conditions of icing in Petrickrepost' area in the environs of Leningrad.

Flying area was located on the northwestern periphery of small cyclone in the zone of occluded front (Fig. 2.20). In flight was observed multilayer cloudiness stratocumulus and altocumulus; in majority its it had the mixed structure, from did not fall the snow.

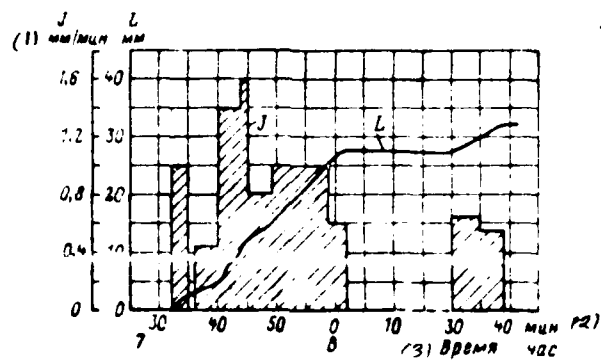


Fig. 2.18. Diagram of icing intensity and curve of the dependence of the thickness of ice, constructed according to data of indicator in flight on 24 April, 1960.

Key: (1). mm/min. (2). min hour. (3). time.

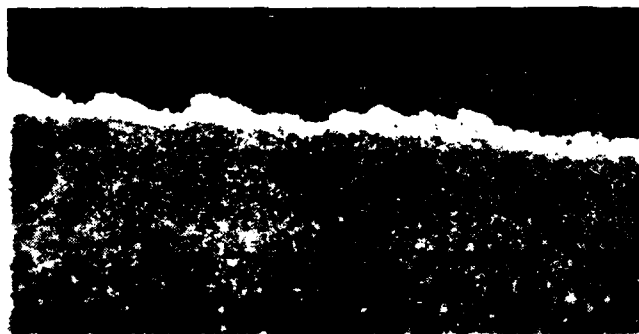


Fig. 2.19. Ice accumulation in section of wing between fuselage and second engine.

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tb flight under conditions of icing is passed at the height/altitude of 3000 m, at indicated airspeed 450-380 km/h and temperature of surrounding air from -10 to -11°C. Icing intensity on indicator maximally reached 3 mm/min (Fig. 2.21). The time of the continuous determination of aircraft under conditions of icing in intensity 2 mm/min and was more 10 min. Ice was formed intermediate form, closer to the first form.

All deicers were connected prior to the entrance into cloudiness. In spite of this, occurred considerable ice formation on the tail assembly and the air intakes of engines¹.

FOOTNOTE ¹. On aircraft tested one of the versions of experimental de-icing system. Series-produced deicing system, established/installed on the aircraft An-10, is distinguished by high effectiveness and provides protection from icing under the assigned conditions.

Flow of moisture from the heated sections of the noses of the tail unit and the air intakes of the engines and the formation of barrier ice were also observed, during the operation of the de-icers.

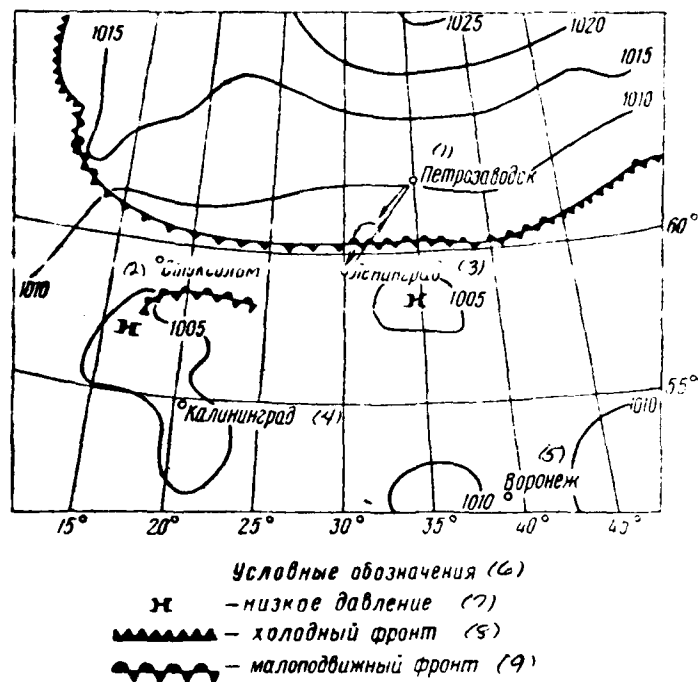


Fig. 2.20. Synoptic situation on 25 April, 1960.

Key: (1). Petrozavodsk. (2). Stockholm. (3). Leningrad. (4). Kaliningrad. (5). Voronezh. (6). Conventional designations. (7). low pressure. (8). cold front. (9). low-mobility front.

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After 20 min of flight under conditions of icing with the working de-icing system the speed of aircraft decreased by 50-60 km/h, which required for retaining/preserving/maintaining the speed transition to higher engine power rating (on 15° on control lever of the fuel consumption).

Example of 5. Experimental flight, carried out on 9 May, 1961, on the aircraft of Tu-104, in period with 16 hours of 35 min to 19 hour of 35 min on route Moscow - Sverdlovsk, passed within the cyclone which had two centers (Fig. 2.22). One center of this cyclone 15 hours was arranged/located in area Moscow and, etc. - in area g. of Kazan. From the center, located in area of Kazan, southwards is passed secondary cold front, and to the southeast - occluded front. In different places of cyclone was noted shower precipitation. The considerable region of precipitation was arranged/located before the occluded front, and frontal cloudiness reached Sverdlovsk. 21 Hours both cyclone centers merged into one, and the occluded front and its region of precipitation and cloudiness they were displaced to the northeast.

Thus, flight considerable time passed under conditions of occluded front.

Icing was encountered 18 hours of 17 min in area of Yanaul in cirrus clouds at the height/altitude of 7700 m at temperature of surrounding air from -32 to -35° C. The speed of aircraft according to instrument was 550 km/h.

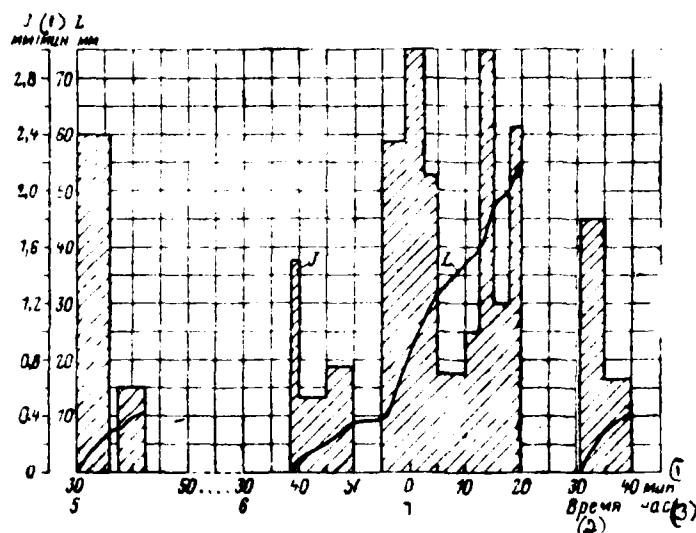
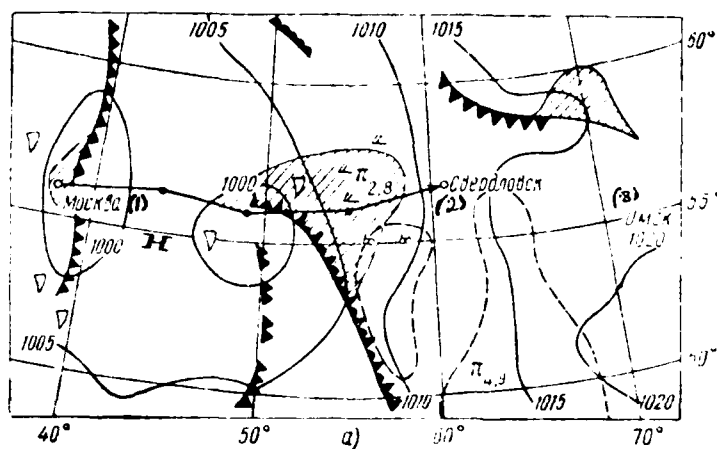


Fig. 2.21. Icing intensity and thickness of ice on standard indicator in flight on 25 April, 1960.

Key: (1). mm/min. (2). time. (3). hour.

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The conventional designations.

----- - warm front.

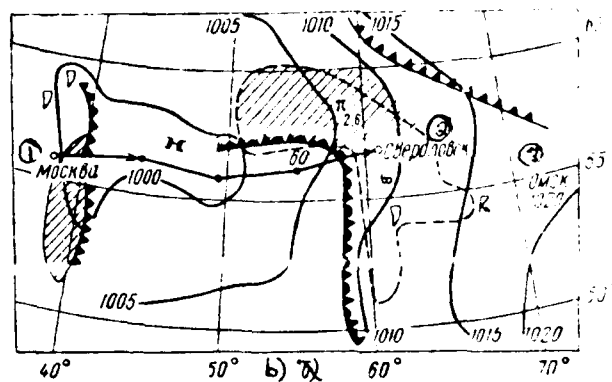
----- - cold front.

----- - occluded front.

∇ - shower precipitation.

H - low pressure.

π - pressure drop.



The conventional designations.

H - low pressure.

—▲— - occluded front.

π - drop of pressure.

R - thunderstorm.

B - cloud of different forms.

D - shower precipitation.

Fig. 2.22. synoptic situation on 9 May, 1961.

a) for 15 hours; b) for 21 hours.

Key: (1). Moscow. (2). Sverdlovsk. (3). Omsk.

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Icing was short-term 2-3 min with intensity of 0.2-0.3 mm/min. Ice in the form of white dense coating. Subsequently the flight was conducted at the heights/altitudes of 7500-6200 m and at indicated airspeed 410-450 km/h.

For a second time aircraft hit the zone of icing at the height/altitude of 6500 m at temperature of surrounding air -23° C in altocumulus clouds. The duration of icing was even shorter-term and it composed only of 30 s.

However, icing intensity reached 6-7 mm/min (on indicator was formed ice with a thickness ~ 3 of mm).

The examined case is interesting that this icing occurred at high altitudes in cirrus clouds and at very low temperatures of surrounding air.

Example of 6. On 5 October, 1961, in flight through Atlantic Ocean in the section of Keflavik - Halifax the aircraft of Il-18 underwent prolonged intense icing at the height/altitude of

approximately/exemplarily 8500 m at very low temperature of surrounding air from -44 to -46° C. True flight speed was 600-620 km/h. For 15-18 minutes of continuous icing on wing was formed ice in thickness approximately 50 mm.

The analysis of surface (Fig. 2.23) and high-altitude (Fig. 2.24) weather map shows that the icing occurred into that moment/torque when aircraft entered into the upper part of the cumulonimbus cloud, which was being formed in the zone of cold front. This was on the anticyclonic side of the jet stream where in this case they were observed both lateral horizontal wind shears and wind shears along flow. The speed of head wind reached 180 km/h.

Icing intensity in recalculation on the indicator of icing was 5-6 mm/min. In this case average/mean water content of clouds reached approximately 0.5 g/m^3 .

Example 7. On 6 October, 1961, passenger turboprop aircraft "Vanguard" of English company VEA, Madrid completed voyage - London, underwent during the climb to extremely intense icing. On this case which deserves detailed description, it was communicated at international conference on the problem of icing [41].

Aircraft icing occurred under conditions of the standing wave

before warm front, which were approaching Madrid (Fig. 2.25). Data of radiosounding of upper air above Madrid, Lisbon and claret showed that on 6 October, 1961, the frontal system was continuous and it had vertical extent approximately/exemplarily to 9000 m. It is characteristic that this day the two additional turboprop aircraft "Viscount" of company VEA they hit under the conditions of intense icing.

Large icing intensity was, obviously, the consequence of the formation/education of the flow of mountain waves and orographic uplift (icing occurred above a Sierra-de-Guadarrama mountains). To an increase in the icing intensity contributed also the fact that the icing occurred near point of occlusion.

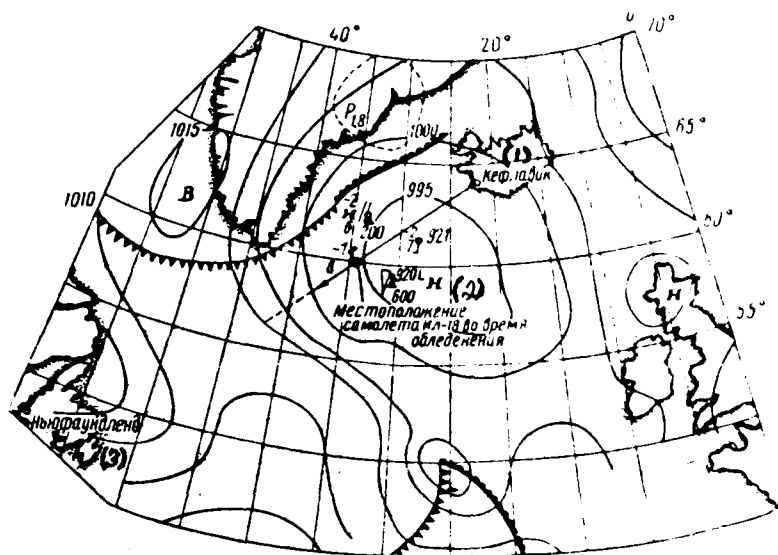
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Aircraft icing "Vanguard", which was continuing for 10-15 min, occurred in the climb in section, approximately/exemplarily, between 2000 and 4200 m at temperature of surrounding air from -10 to -12° C.

According to evidence of crew members, as a result of icing ice was formed on spinners (in water of rings) with a thickness of 50-75 mm in the individual sections of the lower wing surface after the warmed zone (in the form of the ice outgrowths of the irregular form

with a height/altitude of 100-150 mm). Furthermore, icing underwent the unheated end sections of wing, in particular, section in the left navigation light where the thickness of ice achieved 250 mm, and also lateral glass of flight deck. Front/leading glass remained free from ice.

Unheated leading wing edge in the section between the fuselage and inboard engines and tail assembly, unexamined from flight deck, obviously, were also covered with ice of considerable thickness.



The conventional designations.

B - high pressure.

H - low pressure.

∇ - shower precipitation.

▲▲▲▲ - cold front.

◐◐◐◐ - warm front.

9 - five-scale cloudiness, wind 4-6 m/s.

Fig. 2.23. Synoptic situation in 15 hours on 5 October, 1961.

Key: (1). Keflavik. (2). Location of aircraft of Il-18 during icing.
(3). Newfoundland.

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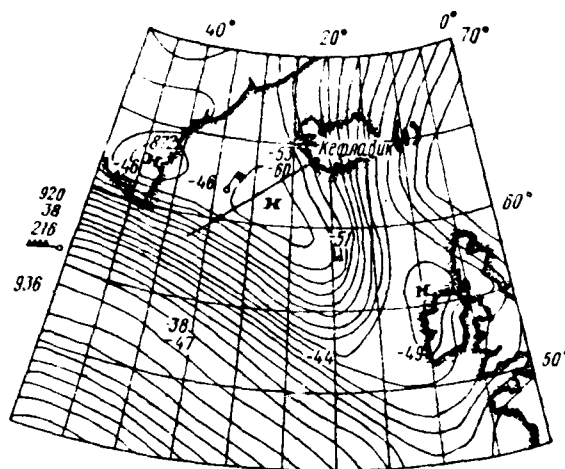
As showed later tests of aircraft "Vanguard" conducted under conditions icing, and also investigation on model airplane, thickness of ice on the leading wing-root edge could reach 200 mm. According to data of experiments ice on the tail assembly was formed and was discarded periodically; however, its maximum thickness could be 130 mm.

Icing underwent also the unprotected numerous projecting elements/cells of aircraft.

The air intakes of engines, apparently, remained free from ice, which is confirmed by the absence of any abnormalities in the operation of engines.

Aircraft began the climb in nominal engine power rating and

indicated airspeed 315 km/h (Fig. 2.26). Upon the entrance into the zone of icing operated/actuated the signal indicator, and crew included/connected the de-icing system of aircraft. As a result of icing, which continued for 10-15 min, the vertical velocity of aircraft continuously decreased and at height/altitude of approximately 5000 m fell to zero despite the fact that the pilot changed engine power rating to takeoff, striving to break clouds and to leave the zone of icing. Indicated airspeed up to this moment/torque decreased to 270-280 km/h appeared the strong agitation of separation character which was perceived on controls.



The conventional designations.

X - low pressure.

— - 14-16 m/s.

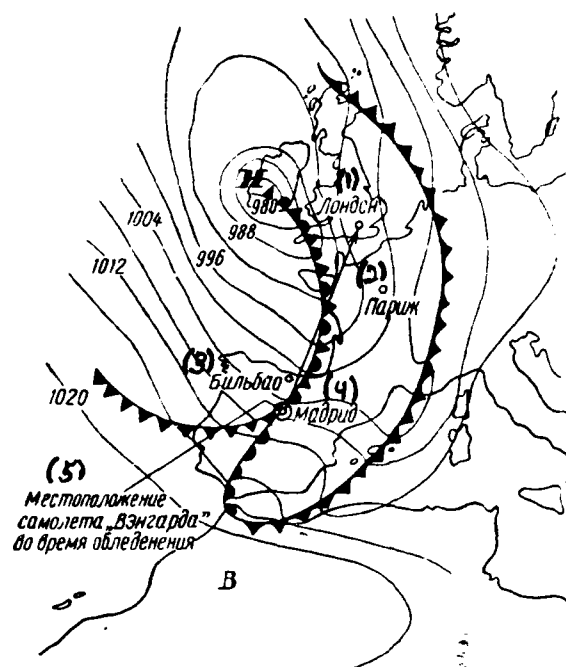
— - 24-26 m/s.

Fig. 2.24. Upper-air chart at 300 mb. in 15 hours on 5 October, 1961, (H=9000 m).

Key (1). Keflavik.

Icing was discontinued, on pilot it was it was forced to transfer aircraft to the mode/conditions of reduction. At the height/altitude of 4270 m the flight continued in takeoff engine power rating, with the connected de-icing system; true airspeed of aircraft at this height/altitude was 410 km/h, which to 235 km/h is less than the flight speed of aircraft under these conditions in the absence of icing.

Ice from aircraft moved away completely only after the flight/span of claret (approximately/exemplarily third of path), after which the de-icing system was switched off, and aircraft, after collecting height/altitude of approximately 6000 m, is continued flight in the normal mode of the work of engines and cruising flight speed.



The conventional designations.

▲▲▲▲ - cold front.

M - low pressure.

B - high pressure.

▲▲▲▲ - occluded front.

Fig. 2.25. Synoptic situation in 15 hours on 6 October, 1961.

Key: (1). London. (2). Paris. (3). Bilbao. (4). Madrid. (5). Location of aircraft "Vanguard" during icing.

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As showed analysis, deterioration in the aircraft performance as a result of icing it required an increase in the power/thickness of engines more than to 40c/o (in comparison with the required power of level flight at the height/altitude of 4270 m at indicated airspeed 330 km/h and $C_D = 0.82$).

Fig. 2.27 gives the polars of uniced and iced up aircraft. As can be seen from graph/curve, the drag coefficient of aircraft C_D at the height/altitude of 4270 m, indicated airspeed 330 km/h and $C_D = 0.82$ it increased by 0.032. 600/o of this drag increment were caused by ice accumulation in thickness to 200 mm on the unheated leading wing-root edges, 150/o - by icing of the tail assembly. The others 250/o are caused by the icing of the lower surface of wing, and also different unheated aircraft components.

In the opinion of firm "Vickers Armstrong", the reason for the emergence of the agitation of aircraft (buffeting) at speed 270-280 km/h was the icing of root of the wing between the fuselage and inboard engines and tail assemblies.

The examined case with aircraft "Vanguard" shows that are possible the extremely severe conditions of icing, although the probability of their meeting is very small.

As showed calculations, liquid-water content in this case was, approximately/exemplarily, 6 times of more than the maximum calculated value of liquid-water content, accepted on English standards, and it comprised, approximately/exemplarily, 3-4 g/m³ with the diameter of droplets 20-40 μ . As the basis of calculation was assumed the maximum thickness of ice, which was being formed on unheated ending of the left main wing and reached 250 mm.

Example of 8. On 31 January, 1963, the aircraft of Il-18, which fulfilled training flights in the adverse weather conditions (landing approaches) in airport zone Vukovo airport at the height/altitude of 400 m, long time was found under conditions of icing.

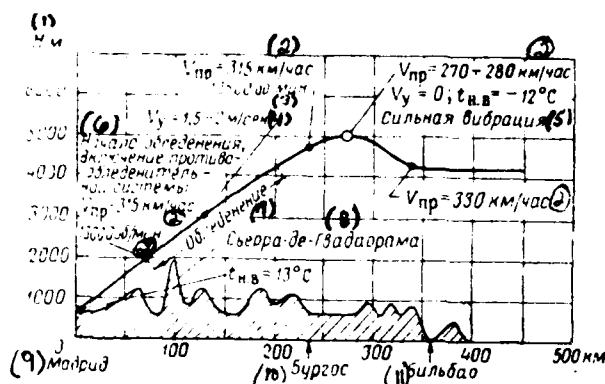


Fig. 2.26. Flight profile of the aircraft "Vanguard" on 6 October, 1961.

Key: (1). Nm. (2). km/h. (3). r/min. (4). m/s. (5). Severe vibration. (6). Began icing, start of anti-icing system. (7). Icing. (8). Sierra-de-Guadarrama. (9). Madrid. (10). Burgos. (11). Bilbao.

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Flight was conducted with 16 hours to 21 hours. In this period of time area Moscow was located under the effect of destructive ridge, and then under the effect of weakly expressed trough and secondary warm front (Fig. 2.28) forming in it. Trough was directed from the cyclone, located in area of Vinnitsa. Warm Secondary front 18 hours passed southeast Moscow in the direction: Kaluga, Serpukhov, Set. Kurovskaya, Vladimir. Before the front were observed the mists, and into the Set. Kubinka and Dmitrov - fog/mist. Front slowly was

moved in the northwestern direction. In the zone of front and before it occurred the formation/education of the cloudiness of lower deck with lower boundary of 100-200 m, while 20 hours in Moscow, st. Chkalovskoy, Bykovo, Narotominsk, sett. Vnukovo, sett. Kubinka and Mozhaysk snow fell.

According to data of aircraft sounding into Vnukovo airport 15 hours stratocumulus clouds were observed at the heights/altitudes of 700 m and 1100-1500 m and altocumulus clouds - at the heights/altitudes of 4500-4800 m.

During sounding the temperature of air in the earth's surface was equal - 10° C, at the height/altitude of 400 m - 12° C, at the height/altitude of 1000 m - 9° C and at the height/altitude of 3000 m - 12° C. Aircraft icing, probably, occurred in cloudiness, under the layer of the inversion whose lower boundary was found at the height/altitude of 400 m. Lower boundary of cloudiness 17 hours was found at the height/altitude of 350 m and 21 hours was dropped/omitted to 120 m. The cloudiness of 10 balls, humidity in period with 15 hours to 21 hours increased from 86 to 97o/o.

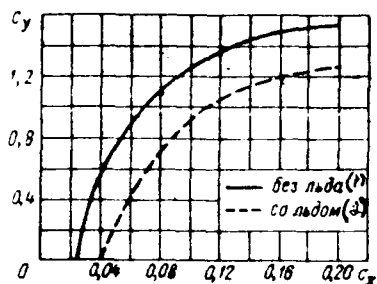


Fig. 2.27.

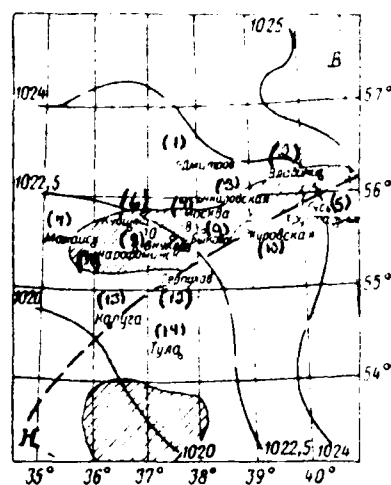


Fig. 2.28.

Fig. 2.27. Polars of aircraft "Vanguard".

Key: (1). without ice. (2). with ice.

Fig. 2.28. Synoptic situation in 20 hours on 31 January, 1963.

Keys (1) Dmitrov. (2) Vladimir. (3) Chkalovskaya. (4) Moscow. (5) Sus' Khrustad [?]. (6) Kubinka. (7) Mazhaysk. (8) Vnukovo. (9) Bykovo. (10) Kurovskaya. (11) Narotominsk. (12) Serpukhov. (13) Kaluja. (14) Tula.

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Fig. 2.29. Icing of nose/leading edge of center section of aircraft of Il-18 in unheated section between air intake of air-air radiator and fuselage.

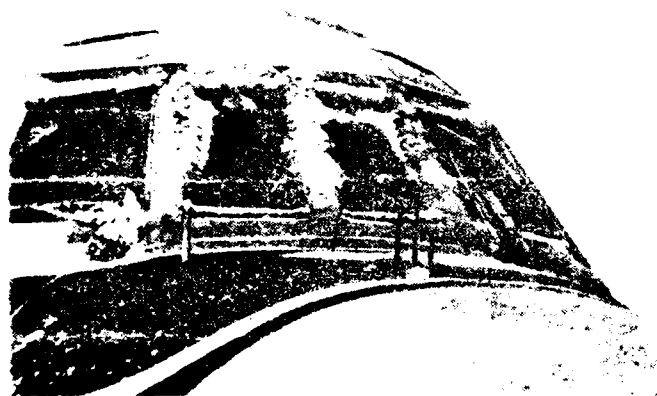


Fig. 2.30. Icing of lamp/canopy of cockpit of aircraft of Il-18.

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Fig. 2.29 and 2.30 depict photo of the root parts of wing and forepart/nose aircraft component. In the unheated section of the center section between fuselage and air intake of air-air radiator entire wing leading edge was covered with ice with a thickness of 30-35 mm, the width of capture was 150-200 mm. On the frames of four front/leading glass of cockpit was formed the layer of ice with a width of 30-40 mm and with a thickness of 50-55 mm. The considerable layer of ice (15-20 mm) was also discovered on the frontal surfaces of the unheated elements of fuselage construction, and also on front/leading and basic landing gear struts.

6. Some hints in accordance with the execution of flights under conditions of icing.

In conclusion let us present several hints to pilot, which will aid it correct to be oriented and to avoid the zones of most dangerous icing.

With preparation and execution of flight it is necessary to focus attention on the following facts:

1. Under what synoptical conditions is passed the route of

flight? In uniform air mass, with the intersection of the fronts or along front?

2. At what heights/altitudes are found upper and lower boundaries of clouds?

3. How is distributed temperature of surrounding air on heights/altitudes and where pass isotherms 0°C and -10°C .

Most frequently the zone of icing is arranged/located between these isotherms.

4. If flight is conducted in clouds of uniform air masses (laminar, stratocumulus, cumulus and cumulonimbus), it is necessary to consider that most intense icing occurs in upper part of these clouds.

In this case upper boundary of stratus and stratocumulus clouds rarely exceeds 2000 m, at the same time the extent (on horizontal) of the zone of icing in these clouds can be very large.

5. If from stratus and stratocumulus clouds falls considerable precipitation in the form of snow, icing intensity in these clouds occurs weak or icing is absent. If precipitation does not fall at all

or they fall in the form of the supercooled drizzle, icing intensity can be the average and even greater.

6. In cumulus and cumulonimbus clouds of uniform air masses icing of large intensity can be encountered at heights/altitudes of 2000-3500 m. In this case the temperature of surrounding air can be considerably below -10°C . Upper boundary of the cumulonimbus clouds can exceed 4000 m.

Is most intense icing in the cumulonimbus and cumulus clouds in spring and autumn periods of year.

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7. In nimbostratus warm-front clouds frequently most intense icing is observed in their lower part where water content of clouds and size/dimension of drops in majority of cases greatest. If warm front is not accompanied by the positive temperatures in the lower part of cloud system, then intersected it should be at the largest possible height/altitude.

→
But if behind front begins warm air with positive temperature in lower part cloudiness, then zone of icing behind front can be located on middle, and sometimes and in upper part cloud system - high zero

isotherm. In this case the flight the front should be carried out at low altitudes, where the temperature of air is positive.

8. Is most dangerous icing in freezing rain, by most frequently connected with warm front. Icing intensity in freezing rain is very large. If aircraft meets freezing rain, then this means that the superincumbent cloud layers have positive temperature. Therefore the rapid climb can derive aircraft from dangerous zone.

9. If warm front is characterized by heavy precipitation in the form of snow and powerful/thick vertical development of cloudiness (to 6000-8000 m), icing in clouds either is absent or, as a rule, it has weak intensity.

10. If warm front is characterized by precipitation in the form of weak snow or drizzles and its cloudiness does not have considerable vertical development, then in clouds is observed icing of large intensity. In this case frequently is formed transparent ice of U-shaped form, which most sharply makes flight aircraft quality/fineness ratios worse.

11. In cumulonimbus cold-front clouds icing can be very intense. Is most intense icing in the upper part of the cloudiness. Therefore intersected front should be either higher than the clouds or, if this

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is impossible, at the low altitudes; it is necessary to keep in mind that the icing in these clouds can occur at very low temperatures of surrounding air.

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Chapter III.

PROTECTION OF AIRCRAFT AND HELICOPTER FROM ICING.

1. Safety methods from icing.

All existing safety methods of aircraft (helicopters) and their power plants from icing can be divided into four groups:

1. Mechanical methods.
2. Physicochemical methods.
3. Thermal methods.
4. Combined methods.

The essence of the first group of methods consists in the mechanical removal of the generatrix of ice on the shielded aircraft

components. One of such methods was widely used during the years 1935-1950 for protection from the icing of wing and tail assembly, but then it was gradually extruded/excluded more advanced.

On some types of foreign aircraft this method is applied at present.

Let us examine briefly the operating principles of the mechanical deicer indicated, depicted schematically on Fig. 3.1. On the leading edge of wing (or tail assembly) are installed rubber protectors, which with switched on deicer fit wing skin. Protectors have the longitudinal chambers/cameras whose quantity can be different. The compressed air initially enters the middle chamber/camera of protector which are blown in and breaks ice formed near leading edge. Then air is released from the middle chamber/camera and is supplied into lateral ones, which, being inflated, break down ice in the lateral sections of nose/leading edge. After this air it is released from lateral chambers/cameras, and cycle is repeated. This alternating filling of the chambers/cameras of protectors with air leads to the breaking of ice into pieces and dropping by its air flow.

For low-speed aircraft the de-icing system indicated upon its timely inclusion provided satisfactory protection in the majority of

the conditions of icing met in flight. However, during the rapid increase of ice (its especially some of forms) protectors proved to be insufficiently effective.

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A fundamental shortcoming in this system is the disturbance/breakdown of the lift-drag ratios of wing and tail assembly, called by a change in the form of the leading edge of an airfoil profile during bulging of protectors. This shortcoming limits the use/application of deicers in some flight conditions (on takeoff, landing) and it makes from virtually unsuitable for contemporary high-speed aircraft.

In spite of the noted shortcomings, to which should be added another possibility of the slight damage of protectors, this system, developed in 1930 by American researchers S. Geer and M. Scott, it played in its time positive role and was the actually first de-icing system which considerably raised safety and regularity of IFR flights.

The physicochemical methods of deicing are based on one of the following principles: 1) the decrease of the cohesive force of ice with the surface of aircraft, 2) depression of the freezing point of water. Essence and each of the groups of the physicochemical methods

consists, thus, in the creation of the interlayer of certain substance between ice and the surface of aircraft shielded by part.

Great attention of the researchers in the initial period of the development of anti-icing means attracted the idea of the creation of this coating, which would possess zero cohesive force with ice.

The method of deicing indicated is extremely tempting. Is actual/real, creation on the surface of the aircraft of the durable permanent or periodically renewed coating, for which it would not be required the supply of any energy and sources, which were being located on aircraft, and which would provide protection from icing, it would most rationally solve entire problem as a whole. However, the numerous attempts, which do not cease and up to now, to develop such coatings were not crowned by success.

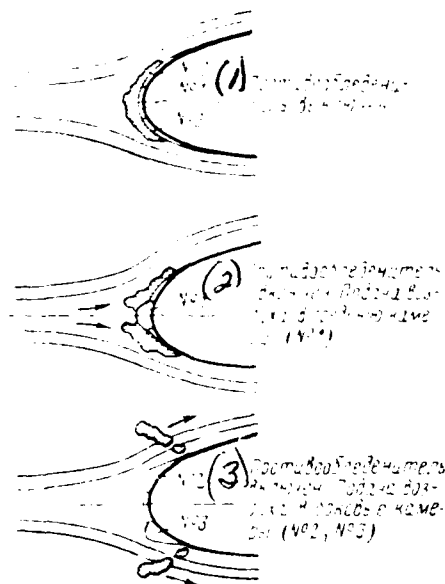


Fig. 3.1. Diagram of the work of mechanical deicer.

Key: (1). Deicer is switched on. (2). Deicer is connected. Air supply into middle chamber/camera. (3). Deicer is connected. Air supply into lateral chambers/cameras.

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was proposed the large number of coatings in the form of varnishes, pastes or lubrications. They all are not yielding positive results. Some of the substances being they are plotted/applied to surface they substantially decreased the cohesive force of its with ice, but this

decrease was nevertheless insufficient for the dropping of ice. It was assumed that effective must prove to be the so-called hydrophobes, i.e., the substances, possessing properties not to be wet by water. As is known, water during incidence/impingement into such substances decays to the spherical drops which are rolled up from the surface, covered with this substance. Such hydrophobes, that possess unwettability or different degree, are, for example, paraffin, petroleum jelly, wax, grease, series/row of silicones. However, experiments showed that the hydrophobicity of substances does not exert of the which decides effects on the process icing. Is explained this by the fact that the supercooled drops with the impact/shock about the surface of aircraft freeze so rapidly that the property of unwettability, apparently, does not manage to be revealed. On the basis of the made experimental works Soviet researcher P. P. Kobeko [9] expressed affirmation, that the strength of freezing water and other liquids to rigid surfaces does not depend on that, is wet surface by this liquid or not. In the opinion of P. P. Kobeko, deciding via the search of the corresponding varnish coating is hopeless.

Nevertheless it should be noted that this categorical point of view can be finally confirmed it and only if will be completely opened physics of the mechanism of the crystallization of the supercooled drops on the surface of the flying aircraft.

To it is ice the built-up edge, which was being formed in flight, for example, on the wing surface, operate the following forces: the force of air pressure, gravitational force, cohesive force of ice with wing skin. The latter plays the dominant role and in its value considerably exceeds the others. This showed experiments the study of the protective coatings about which it was mentioned above. The cohesive force (adhesion) of ice with the surface of metal is the result of the molecular attraction of these bodies and their ganging (as a result of the roughness of contact surface). This cohesive force of ice of different form with the wing surface depends on a number of factors. Its value can reach 10 kgf/cm² and more. In connection with the fact that attempts to remove or into a sufficient measure to decrease this cohesive force thus far not of yielding positive results the researchers turned to the second direction into the development of the physicochemical methods of icing of aircraft, namely to the coatings, lowering the freezing point of water.

The idea of creation on the surface of the aircraft of coating from the substance, readily soluble in water and which forms the nonfreezing solution/opening during incidence/impingement to it from air of the supercooled drops of water, was conceived even in the

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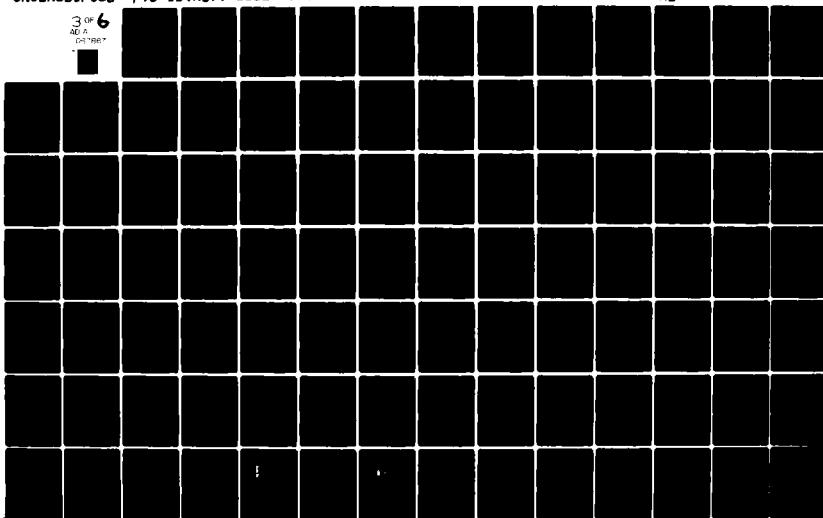
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beginning Thirties. As such substances can, for example, serve calcium chloride, nitric acid sodium, sodium chloride, ethylene glycol, etc.

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Experiments showed that such substances, plotted/applied (in mixture with other connections) to the surface of aircraft, contribute to the elimination on it of icing. The usually supercooled drops of water, falling from the atmosphere to the surface, covered with this substance, as a result of the large crystallization rate manage to freeze and to form the film of ice. However, that part of ice, which directly comes into contact with the surface of aircraft, begins to be melted, the cohesion/coupling ice is disrupted and ice crust drops, without having achieved considerable thickness. Then process is repeated.

Main disadvantage in this method, which restricted its practical use/application, is the short duration of the action of all substances indicated, since they are removed together with the stripped ice built-up edge, and also easily they wash off under the action of rain. For eliminating this shortcoming were developed the deicers, which provided the continuous feed of substance (usually liquid) to the shielded surface. In their time received certain

propagation the devices/equipment, which made it possible to continuously wet the shielded surface by anti-icing liquid by its liberation through porous skin. At present on some aircraft is applied for the same purpose porous metal. Wide acceptance received the liquid deicers for propellers, used up to now on working piston-engined aircraft.

The mechanism of the action of the liquid substance, continuously supplied to the surface shielded from icing, is somewhat different from the mechanism of the application of solid or pastelike anti-icing coating. If in the latter case occurs the periodic formation/education of ice crust, then its slight melting and dropping, then the anti-icing liquid, which enters, for example, to frontal glass of cockpit, at a sufficient rate of its supply, simply washes off the settling supercooled drops, without giving to them to be crystallized.

It should not be supposed that the anti-icing liquid effectively melts forming ice. Laboratory tests showed that during insertion into the vessel, filled with alcohol, the cube of ice, the time of its complete melting is approximately 40 min [4]. Hence follows and this confirms practice that the liquid de-icing systems are more effective as the means, antiicing, but not as the means, which removes the formed layer of ice. The lower freezing point of liquid and than more

it is polar, the better the liquid it melts ice. Thus, anti-icing liquid exerts on ice both chemical and mechanical influence. To this frequently is added thermal effect, since the liquid entering sometimes has positive temperature.

A fundamental shortcoming in all liquid de-icing systems is the limitedness of their action on time.

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The need for having on board aircraft a considerable reserve of liquid, and also a complexity of constructing/designing such systems for large aircraft throttled/tapered region their uses/applications: liquid deicing systems were utilized mainly for the protection of glasses of the flight deck and propellers. The typical pattern of this system, which was being applied on piston-engined aircraft, it is shown in Fig. 3.2.

For a wing and a tail assembly liquid systems were applied rarely. As an example it is possible to give English aircraft Vickers "Viking", whose liquid de-icing system was established/installed on wing and tail assembly. According to the data of tests [34], carried out into 1950, flow rate of anti-icing liquid, which was being required for protection from the icing of the aircraft components

indicated, it did not exceed 6 l/h/m². Supply to liquid to the shielded surface was accomplished/realized through special porous coatings. This explains comparatively low fluid flow rate (for example, for glasses of aircraft Li-2 the flow rate of fluid comprised in average/mean 8-10 l/h). Although the system was included prior to the beginning of icing, it worked actually as an ice remover, periodically allowing/assuming ice formation of small thickness and then dumping it. Upon the inclusion of system after the entry into the zone of icing, the time, necessary for the first jettisoning of ice, it reached the significant magnitude: at temperature of surrounding air of -3°C for the removal of ice in thickness ~6 mm, stabilizer formed on leading edge, were required more than 10 min. at low temperature this time increased even more.

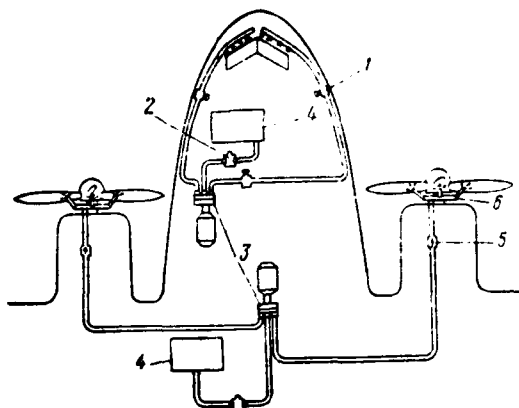


Fig. 3.2. The typical pattern of the liquid de-icing system of propellers and glasses. 1 - stop cock, 2 - filter, 3 - pump, 4 - block for an anti-icing liquid, 5 - check valve, 6 - distributive ring on propeller.

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In spite of essential shortcomings in the liquid de-icing systems, work on their improvement are continued also at present. It was in particular communicated [58] that as a result of an improvement in the distribution of liquid according to the shielded surface, it was possible to considerably reduce its flow rate. The English firm TKS continues investigations and development of liquid de-icing systems both for the aircraft and for helicopters. Fig. 3.3 gives the overall diagram of the liquid de-icing system of aircraft.

System works as periodic deicer and is based on the decrease of the cohesive force of ice with the surface, moistened by the liquid, which reduces the freezing point of water. With an increase in the thickness of the forming ice built-up edge the force of the effect on it of air flow increases and, if to the internal surface of a layer of ice through porous skin/sheathing continuously is fed/conducted anti-icing liquid, then comes this moment, when aerodynamic forces overcome the cohesive force of ice and it is dumped. The cyclic recurrence of the action of this deicer depends on a number of factors: the speed of ice formation, temperature of surrounding air, form of ice, speed of the aircraft (main role play temperature and icing intensity). Anti-icing liquid is fed/conducted to the shielded surface of wing or tail assembly with the aid of special distributive panels from porous metal. Are applied two versions of the construction/design of the nose/leading edge of deicer. In the first version two longitudinal narrow panels are installed flush with skin/sheathing on both sides from leading edge.

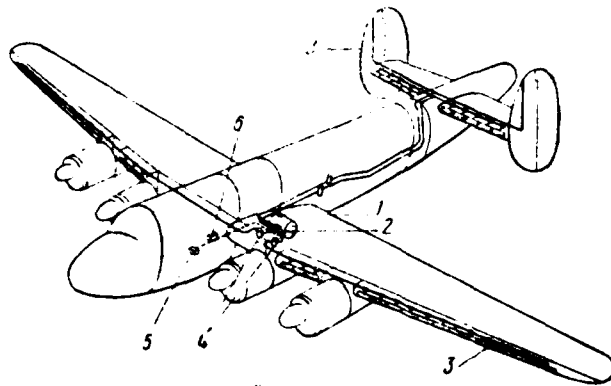


Fig. 3.3. Overall diagram of the liquid de-icing system of aircraft.
1 - tank with anti-icing liquid, 2 - pump, 3 - porous nose/leading edge of deicer, 4 - filters, 5 - switch, 6 - regulator.

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Liquid leaks through porous diaphragms of panels and spreads over the surface of nose/leading edge. A shortcoming in this version is the fact that between panels on leading edge sometimes remains the ice built-up edge which holds there sufficiently prolonged time. The second version, in which entire nose/leading edge is made from porous metal, is deprived of this shortcoming; however, in this case appear the difficulties of guaranteeing the even distribution of liquid with its required low flow rate. For achievement this under porous skin/sheathing is installed porous elastic material "Porvik", which creates necessary hydraulic flow resistance of liquid and, thus,

provides its uniform very low flow rate through external porous skin/sheathing.

Fig. 3.4, borrowed from work [58], schematically shows the construction/design of the liquid deicer, established/installed in the wing leading edge.

As metal for distributive panels at first were applied porous bronze "Porosint", and then porous stainless steel.

For anti-icing liquids is presented the series/row of the requirements: liquid must have low freezing point, a good miscibility with water, liquid must not be toxic, cause the corrosion of the aircraft components and damage of its paint and varnish coats. The liquids, used for protection from the icing of wing and tail assembly, are usually based on glycols. For example, the English liquid R-328. For protection from the icing of glasses of cockpit widest use received ethyl and isopropyl alcohol¹.

FOOTNOTE ¹. Glycol liquids for the protection of glasses cannot be used, since they make visibility worse. ENDFOOTNOTE.

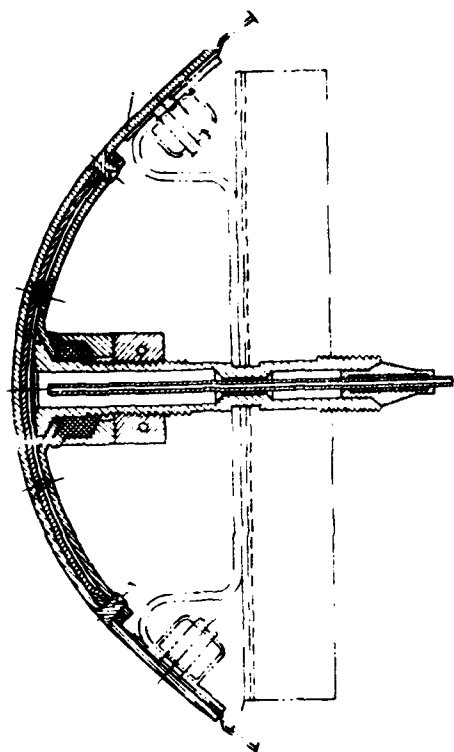


Fig. 3.4. Construction/design of the liquid deicer of the wing leading edge.

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Are of interest some data according to the flow rates of the anti-icing liquid R-328 for the protection of wing on the following aircraft types:

Vickers a "Viking" - 500 cm³/min;¹

FOOTNOTE 1. The improved de-icing systems, established/installed on these aircraft, have considerably smaller flow rate it is related to page 90. ENDFOOTNOTE.

De Haviland "Dov" - 226 cm³/min;¹

Avro "Shackleton" - 354 cm³/min;

Scotch Aviation "Twin Pioneer" - 189 cm³/min.

On jet De Haviland - 125 for protection from the icing of wing and tail assembly is applied liquid de-icing system with the average/mean fluid flow rate of altogether only of 1.6 l/m² in hour. As showed flight tests, system worked effectively. The improvement of liquid de-icing system makes it promising for some aircraft types.

Besides protection from the icing of the wing of tail assembly, cockpit windows, propellers, were done the attempts to use liquid de-icing system, also, for engines and their air intakes (in particular for engines "Dart"). However, these systems did not win acceptance.

Considerable works were carried out on the use/application of liquid de-icing systems on helicopters. Such systems were, for example, they were established/installed on the Soviet helicopters of Mi-1 and Mi-4 for protection from the icing of the blades/vanes of the carrying and tail rotors.

The third group of safety methods of aircraft from icing which will be in this chapter examined most in detail, is based on the use of thermal energy, developed either by the engines of aircraft or with special installations.

Besides the enumerated three basic groups, sometimes are applied the combined methods of deicing. For example, the combination of mechanical and physicochemical methods.

2. General/common/total static data along the de-icing systems of aircraft.

Let us examine some general/common/total statistical data along the de-icing systems of contemporary transport aircraft with gas turbine (TRD and TVD) and piston (PD) engines (table 6).

In table 6 is contained the information according to 48 aircraft types which are operated at present into the USSR, USA, England,

France and Holland.

As can be seen from table 6 for wing and tail assembly of aircraft with GTD [gas-turbine engine] and PD in the overwhelming majority of the cases (68 cases or 105)¹ is applied the air-heat de-icing system.

FOOTNOTE ¹. Numeral 105 encompasses the total number of the de-icing systems (wing and tail assembly) of 48 aircraft types taking into account the versions of systems. ENDFOOTNOTE.

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The operating principle of system is based on the use either of hot air, taken from the compressors of engines or the air, heated in heat exchangers by the hot exhaust gases circulating in them. Preheating air sometimes also is accomplished/realized with the aid of special gasoline preheaters.

The protection of wing and tail assembly from icing by mechanical and physicochemical methods is applied in essence only on aircraft with PD. For the protection of the tail assembly of aircraft with GTD widely is applied thermoelectric de-icing system (11 cases), whereas for a wing it was used altogether only in two cases.

Should be also noted the fact that in spite of advantageous use for the de-icing systems of aircraft with GTD of the hot air, selected/taken from the compressors of engines, for turboprop aircraft is frequently utilized the heating by the air, heated by waste heat (in heat exchangers), as, for example, on aircraft "Viscount", "Britain", "Vanguard". The selection of this system of heating is dictated, in essence by the impossibility of the selection of the air required a quantity from the compressor of turboprop engine as a result of a considerable reduction/descent in its power. However, for aircraft with the turbojet engines, which allow/assume the selection of a larger quantity of air, the use/application of heat exchangers it is not characteristic.

For protection from the icing of the tail assembly of aircraft with PD just as for a wing, are applied mechanical (6 cases) and physicochemical methods (5 cases).

For engines and their air intakes in essence is applied the air-heat system; in 4 cases is used the thermoelectric system of cyclic action (for air intakes) and only in one case of the physicochemical action.

For the protection of the screws/propellers and coaks from icing are applied the electrical heating (19 cases), and also physicochemical safety methods (9 cases), moreover for some aircraft with PD characteristically generally the absence of de-icing system for the screws/propellers (ice from them is removed by changing the propeller pitch).

Most widely used safety method of glasses of cabin/compartment from icing is electrical heating (32 cases), are applied also chemical method (8 cases) and hot-air heating. In two cases is noted the use of de-icing system of glasses of the combined action; fundamental air-heat and auxiliary liquid.

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Table 6. The de-icing systems, which are applied on contemporary passenger aircraft.

(2) Тип самолета	(3) Двигатель	(4) Полетный вес кг	(1) Про (5) крыла
Ту-104	2 ТРД РТ-3М	$G_{пол} = 76\,000$ $G_{вес} = 61\,000$	С С (10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателей
Ту-124	2 ТРД 1-20Н	$G_{пол} = 34\,500$ $G_{вес} = 30\,000$	(10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателей
Ил-20	2 ТРД ВК-1	$G_{пол} = 21\,000$ $G_{вес} = 13\,700$	(10) Воздушно-тепловая с соров двигателей
Ил-18	4 ТВД АН-20 с винтами АВ-68Н	$G_{пол} = 59\,200$ $G_{вес} = 61\,500$ $G_{вес} = 46\,000$ $G_{вес} = 51\,000$	(14) Электротепловая цик
Ту-114	4 ТВД НК-12МВ с винтами АВ-60Н	$G_{пол} = 164\,000$ $G_{вес} = 128\,000$	(14) Электротепловая цик
Ан-10	4 ТВД АН-20 с винтами АВ-68Н	$G_{пол} = 54\,000$ $G_{вес} = 50\,000$	(10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателей
Ан-24	2 ТВД АН-24 с винтами АВ-72	$G_{пол} = 19\,500$ $G_{вес} = 18\,800$	(10) Воздушно-тепловая с соров двигателей
Ил-14	2 ПД АН-82Т с винтами АВ-50	$G_{пол} = 17\,500$	(18) Воздушно-тепловая с менников
Ил-12	2 ПД АН-82 ФН винтами АВ-9В	$G_{пол} = 16\,100$	(20) Воздушно-тепловая с применением теплообменников

continuation.

Теплообеспечительная система			
(6) оперения	(7) двигателей и воздухо-заборников	(8) винтов и коков	(9) стекло кабины
С Р			
(11) Электротепловая циклического действия	(10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателей		(12) Электротепловая
(11) Электротепловая циклического действия	(10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателей		(12) Электротепловая
	использованием горячего воздуха от компрессоров		(13) Электротепловая
лического действия	(15) Воздушно-тепловая воздухозаборников и лопаток ВНА. Ребра картера обгреваются горячим маслом	(14) Электротепловая циклического действия	(13) Электротепловая
лического действия	(17) Воздушно-тепловая воздухозаборников и лопаток ВНА. Ребра двигателя обгреваются горячим маслом	(16) Электротепловая циклического действия	(13) Электротепловая
(11) Электротепловая циклического действия	(15) Воздушно-тепловая воздухозаборников и лопаток ВНА. Ребра картера обгреваются горячим маслом	(16) Электротепловая циклического действия	(13) Электротепловая
	использованием горячего воздуха от компрессоров	(16) Электротепловая циклического действия	(13) Электротепловая
применением теплообменника	(19) Всасывающая система двигателей обогревается теплым воздухом		(13) Электротепловая
(21) Воздушно-тепловая с применением бензоподогревателя			(13) Электротепловая

continuation.

Ан-14	2 ПД АН-14РФ с вин- тами ЗСМВ-4	(13)	$G_{\text{вкл}} = 3270$	(20) Воздушно-тепловая с менников
Ан-2	2 ПД АН-62НР с вин- тами АВ-7Н-161	(13)	$G_{\text{вкл}} = 10700$	(20) Воздушно-тепловая с применением теплооб- менников
(24) Боинг 707 (707-120)	4 ТРД (25) Пратт-Уитни J-57	(25)	$G_{\text{вкл}} = 104300;$ 112000 $G_{\text{топ}} = 74800;$ 79400	(10) С Ш Воздушно-тепловая с использованием горяче- го воздуха от компрес- соров двигателей
Дуглас DC-8 (27)	4 ТРД Конвэр J-75 (28)	(28)	$G_{\text{вкл}} = 130400;$ 130680 $G_{\text{топ}} = 86410;$ 86590	(10) Воздушно-тепловая с соров двигателей
Боинг 727 (24)	3 ТРД Пратт-Уитни J78D-1	(25)	$G_{\text{вкл}} = 64400$ $G_{\text{топ}} = 59400$	(30) Воздушно-тепловая
(31) Конвэр "Скайларк" 600 "Дженерал Элект- роник" "Голден трик CV-805 эпрон"	4 ТРД (32) Пратт-Уитни РТ-2(T-34)	(32)	$G_{\text{вкл}} = 92340;$ 92200 $G_{\text{топ}} = 70300;$ 70370	(10) Воздушно-тепловая с использованием горяче- го воздуха от компрес- соров двигателей
(35) Бокад "Супер Сун- пер Констелл- сини" (L- 1449)	4 ТВД (25) Пратт-Уитни РТ-2(T-34)	(25)	$G_{\text{вкл}} = 80300;$ 78400 $G_{\text{топ}} = 56700;$ 56000	(10) Воздушно-тепловая с го воздуха от компрес
(36) Дуглас "Каргомастер" С-133А	4 ТВД (25) Пратт-Уитни Т34-Р-3А "Гурбо- Уосп" (37)	(25)	$G_{\text{вкл}} = 115670$	(38) Воздушно-тепловая циклического действия с использованием горя- чего воздуха от ком- прессоров двигателей

continuation.

менением теплооб-	(22) Карбюратор обогревается теплым воздухом из-под капотного пространства	(12) Электротепловая
(21) Воздушно-тепловая с применением бензоподогревателя	(23) Карбюратор обогревается теплым воздухом	(12) Электротепловая
(12) Электротепловая	(10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателя	(26) Электротепловая (стекла NESAs)
использованием горячего воздуха от компрессоров двигателя		(29) Электротепловая (NESAs). Защита от дождя с помощью струй воздуха от системы кондиционирования
		(12) Электротепловая
(33) Электротепловая фирмы Гудрич	(34) Воздушно-тепловая с использованием воздуха от компрессоров двигателей	(26) Электротепловая (стекла NESAs)
использованием горячих компрессоров двигателей		(12) Электротепловая
(37) Механического действия - пневматические протекторы	(10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателей	(16) Электротепловая циклического действия
		(12) Электротепловая

continuation.

(40) Lockheed "Electra" (SS and ISS)	1 ТВД Аллисон 501-113А (44)	$G_{\text{взд}} = 19\ 900$; $G_{\text{гор}} = 51\ 260$; $G_{\text{вос}} = 42\ 360$; 12 350	(10) Воздушно-тепловая с использованием горяче- го воздуха от компрес- соров двигателей
(43) Lockheed C-130A или 130B	1 ТВД Аллисон Т56-А-7А (44)	$G_{\text{взд}} = 61\ 200$ $G_{\text{вос}} = 58\ 000$	(P) Воздушно-тепловая с соров двигателей
(44) Дуглас "Супер" DC-3	2 ПВД (25) Прайт-Уитни R-2000-15	$G_{\text{взд}} = 14\ 000$	(45) Механического дейст Гудрич
(49) Мартин 202	2 ПД (60) 202 Меркури	$G_{\text{взд}} = 18\ 600$ $G_{\text{вос}} = 16\ 555$	(51) Воздушно-тепловая с менников или использо ных газов (на 1 м ² под
(49) Мартин 101	2 ПД (25) Прайт-Уитни CB-17 2 ТВД (44) Аллисон Т-38	$G_{\text{взд}} = 20\ 400$ $G_{\text{вос}} = 19\ 500$	(32) Воздушно-тепловая с гревателей
(53) Фарманн С-82 "Пакет"	2 ПД (25) Прайт-Уитни R-2800-С Дабл- Уосп (54)	$G_{\text{взд}} = 22\ 680$ $G_{\text{вос}} = 21\ 430$	(30) Воздушно-тепловая
(55) Lockheed "Конквест" C-130	1 ПД (56) Райт Циклон 789С, 18-12.11.11 Прайт- Уитни Дабл- Уосп CA-15	$G_{\text{взд}} = 47\ 670$ $G_{\text{вос}} = 38\ 400$	(45) Механического дейст Гудрич
(27) Дуглас C-130B	1 ПД (25) Прайт-Уитни R-2800; CB-16	$G_{\text{взд}} = 45\ 360$ $G_{\text{вос}} = 40\ 010$	(30) Воздушно-тепловая

continuation.

(42) I вариант--электро-тепловая; II вариант--воздушно-тепловая с отбором воздуха от двигателей	(10) Воздушно-тепловая с использованием горячего воздуха от компрессоров двигателей	(12) Электро-тепловая	(26) Электротепловая (стекла NES)
использованием горячего воздуха от компрес-	(12) Электро-тепловая	(12) Электротепловая	
вия--протекторы фирмы	(46) Жидкостная (карбюратора)	(47) Жидкостная	(48) Основная воздушно-тепловая (от системы отопления кабины) и вспомогательная--жидкостная
применением теплооб- ванием тепла выхлоп- водится 4000 ккал/час)		(12) Электро-тепловая	(12) Электротепловая
применением бензообо-		(12) Электро-тепловая	
		(47) Жидкостная	(30) Воздушно-тепловая
вия--протекторы фирмы		(47) Жидкостная	(12) Электротепловая

continuation.

(37) Avias DC-6 4 ПД (57) Пратт-Уитни "Лабел-Уосп" R-2800; C-1A-15	$G_{max} = 38\ 000$ $G_{min} = 33\ 000$	(38) Воздушно-тепловая
(37) Avias DC-7 4 ПД (59) Пратт-Уитни "Уосп-Ментжор" R-2800	$G_{max} = 73\ 500$	(39) Воздушно-тепловая с мешиников
(40) Боинг 377 "Стратокру- сер" 4 ПД (59) Пратт-Уитни "Уосп-Ментжор"	$G_{max} = 59\ 000$ $G_{min} = 47\ 600$	(39) Воздушно-тепловая
(41) Де Хэвил- ленд "Коме- та" 4 4 ТРД Эвон 525 (62)	$G_{max} = 70\ 760$ $G_{min} = 69\ 200$ $G_{max} = 51\ 250$ $G_{min} = 53\ 750$	(63) А Н Г (40) Воздушно-тепловая с соров двигателей
(44) Виккерс VC.10 4 ТРД (65) Роллс-Ройс "Конквин"	$G_{max} = 152\ 800$ $G_{min} = 135\ 600$	(40) Воздушно-тепловая с соров двигателей
(67) Де Хэвил- ленд ДН 121 "Грайтент" 3 ТВРД (68) Роллс-Ройс "Спей" RB 163-1	$G_{max} = 48\ 534$ $G_{min} = 42\ 266$	(69) Воздушно-тепловая с го воздуха от компрес- стема рассчитана на по- виях обледенения до го воздуха равной ми
BAK-III 2 ТВРД (68) Роллс-Ройс "Спей" RB 163-1	$G_{max} = 31\ 000$ $G_{min} = 33\ 400$ $G_{max} = 29\ 500$	(40) Воздушно-тепловая с соров двигателей

continuation.

	(58) I вариант-жидкостная; II вариант-электротепловая	(47) Жидкостная
применением теплооб-	(P) Электро-тепловая	(30) Воздушно-тепловая
	(12) Электро-тепловая	(12) Электротепловая
для		(12) Электротепловая
использованием горячего воздуха от компрес-		
использованием горячего воздуха от компрес-		(66) Электротепловая (стекло состоит из: внешнего закаленного стекла, золотой пленки, тонкой прослойки из поливинилбутираля и основного сподового стекла
использованием горяче-	(70) Воздушно-тепловая с использованием горяче-	(P) Электротепловая
соров двигателей. Си-	го воздуха от компрес-	
парение влаги в усло-	соров двигателей. Си-	
температуры наружне-	стема работает автома-	
нос 40° C	тически и может вклю-	
	чаться при рулении и	
	взлете	
использованием горячего воздуха от компрес-		(P) Электротепловая

continuation.

(77) Виккерс "Ванкаут" 800-810	4 ТВД Дарт R.1а6 (72)	$G_{взл}=29\ 500$; 28 100 $G_{нос}=25\ 855$; 27 690 $G_{взд}=30\ 600$; 31 300	(73) Воздушно-тепловая с применением теплооб- менников
(75) Бристоль "Британия" серия 310	4 ТВД Протей 755 (76)	$G_{взл}=74\ 800$; 79 300	(78) Воздушно-тепловая с применением теплооб- менников
(78) Виккерс "Вэнгард"	4 ТВД (77) Роллс-Ройс "Тайн"	$G_{взд}=64\ 000$ $G_{нос}=54\ 900$	(80) Воздушно-тепловая с применением теплооб- менников, размещенных в гондолах двигателей
(84) Армстронг Уитворт AW.650 "Аргосин"	4 ТВД (85) Роллс-Ройс "Дарт" Mk. 526	$G_{взд}=39\ 900$ $G_{но.}=36\ 300$	(82) Воздушно-тепловая, с применением теплооб- менников
(87) Британн SO-30P	2 ПД (85) Пратт-Уитни 2800 B-43	—	(86) I вариант — механиче II вариант — воздушно
(90) Скоттман Эвизэши, Гуни Оливис, Тесон- Пайонир	2 ПД (91) дес 502 I	$G_{взд}=6125$	(92) I вариант — жидкостн II вариант — механиче
(95) Де Хэвил- ленд "Дав"	2 ПД (96) Де Хэвилленд "Джипси Квин" 71 3 ПВД "Джипси Менджер"	$G_{взд}=3855$	(94) Жидкостная (TKS)
(97) Авро "Норк" 685	4 ПД (98) Роллс-Ройс "Мерлин" XX	$G_{взд}=29\ 500$	(94) Жидкостная (TKS)

continuation.

(73) Электротепловая циклического действия (покрытие "Спреймат" фирмы Нэпир)	(74) Электротепловая циклического действия (система фирмы Данлоп) - воздухозаборников	(12) Электротепловая	(26) Электротепловая (стекла NESAI)
(73) Электротепловая циклического действия (покрытие "Спреймат" фирмы Нэпир)	(74) Электротепловая циклического действия (система фирмы Данлоп) воздухозаборников	(12) Электротепловая	(12) Электротепловая
(73) Электротепловая циклического действия (покрытие "Спреймат" фирмы Нэпир)	(81) Электротепловая циклического действия (система фирмы Данлоп) воздухозаборников и воздушнотепловая с использованием горячего воздуха от компрессоров двигателей - входных устройств двигателей	(82) Электротепловая циклического действия	(82) I вариант - электротепловая (стекла NESAI и триплекс с золотой пленкой) II вариант - жидкостная
(73) Электротепловая циклического действия (покрытие "Спреймат" фирмы Нэпир)	(74) Электротепловая циклического действия (система фирмы Данлоп) воздухозаборников	(86) Электротепловая циклического действия (система фирмы Данлоп)	(26) Электротепловая (стекла NESAI)
ская фирмы Гудрич; тепловая			(89) I вариант - жидкостная II вариант - воздушнотепловая
ия (TKS) ского действия	(93) Всасывающая система двигателей обогревается горячим маслом	(84) Жидкостная (TKS)	
		(94) Жидкостная (TKS)	(47) Жидкостная
			(47) Жидкостная

continuation.

(99) Веккер VC.12 2 ПД (100) Викинг Бристоль Гер- кулес 634	$G_{вкл} = 14970$	(94) Жидкостная (TKS)
(101) Хэнли 4 ПД (102) Пейсик Ма- Де Хэвилленд рафон Лансен Кинг 71	$G_{вкл} = 8465$	(90) Воздушно-тепловая
Хэнли 4 ПД Пейсик Гер- Бристоль Гер- кулес 101 (105) (106)	$G_{вкл} = 31000$	Жидкостная (TKS) (94)
Эрлинг 2 ПД Амбассадор Бристоль Пентавр 661 (107) (108)	$G_{вкл} = 21000$	(106) Воздушно-тепловая с тепей
(111) SNCA SE 210 2 ПД (112) Каравелла Ролле-Рон Эммануэль	$G_{вкл} = 17000$ $G_{дв} = 13500$ $G_{дв} = 14750$ $G_{дв} = 11500$	(113) ФРАН (10) Воздушно-тепловая с соров двигателей
(114) Давидок 161 4 ПД (115) Гном-Рон 11 № 11 45		(45) Механического дейст Гудрич
(116) Бреск 800 2 ПД Амбассадор 211 (117)		(118) I вариант - механиче ма Клебер-Колэмб; II вариант - воздушно- ным бензоподогревате
(119) Фоккер F-27 2 ТВД (120) Бристоль Ролле-Рон Дарт 541	$G_{вкл} = 15660$ $G_{дв} = 16200$ $G_{вкл} = 14970$ $G_{дв} = 15400$	(121) ГОЛЛ (122) I вариант - воздушно- тепловая с использова- нием тепла выхлопных газов; II вариант - механи- ческого действия - про- екторы фирмы Гудрич

continuation.

	(47) Жидкост- ная	(47) Жидкостная
(103) Карбюратор обогре- вается горячим маслом	(47) Жидкост- ная	(104) Воздушно- тепловая и жидкостная
	(58) I вари- ант жид- костная II вари- ант элект- роотепло- вая	Жидкостная (47)
применением обогрева	(58) I вари- ант жид- костная II вари- ант элект- роотепло- вая	(104) I вариант электроотепло- вая II вариант жидкостная
ция		(47) Жидкостная
использованием горячего воздуха от компрес-		
ния - протекторы фирмы		
того действия: систе- матическая с примене- нием	Жидкост- ная (47)	
АНДИЯ Электроотепловая цик- лического действия (по- крытие "Спреймат" фирмы Нэпир)	(12) Электро- тепловая	(12) Электроотеп- ловая

Key: (1). De-icing system. (2). Aircraft type. (3). Engine. (4). Gross weight kg. (5). wing. (6). tail assembly. (7). engines and air intakes. (8). screws/propellers and cools. (9). glasses of cabin/compartment. (10). Air-heat with use of hot air from compressors of engines. (11). thermoelectric of cyclic action. (12). Electrothermal. (13). with screws/propellers. (14). Thermoelectric of cyclic action. (15). Air-heat - air intakes and blades VNA. The edges/fins of crankcase are warmed by hot oil. (16). Thermoelectric of cyclic action. (17). Air-heat of air intakes and blades VNA. The edges/fins of engine are warmed by hot oil. (18). Air-heat from exchangers. (19). Exhaust system of engines is warmed by warm air. (20). Air-heat with use/application of heat exchangers. (21). Gasoline heaters of air-heat with use/application. (22). Carburetor is warmed by warm air from under hood space. (23). Carburetor is warmed by warm air. (24). Boeing. (25). Pratt-Whitney. (26). Thermoelectric (glass NES). (27). Douglas. (28). Conway. (29). Thermoelectric (NES). Protection from rain - with the aid of air jets from the system of conditioning. (30). Air-heat. (31). Convair "Skylark" 600 (or "Golden Arrow"). (32). General Electric. (33). Thermoelectric of firm Goodrich. (34). Air-heat with use of air from compressors of engines. (35). Lockheed "Super Constellation". (36). Douglas "Cargomaster". (37). Turbo-Wasp. (38). Air-heat of cyclic action with use of hot air from compressors of engines. (39).

Mechanical action - pneumatic protectors. (40). Lockheed "Electra" 88 or 188). (41). Allison. (42). I version - thermoelectric; II version - air-heat with air bleed from engines. (43). Lockheed C130A or 130B. (44). Douglas "super". (45). Mechanical action - protectors of firm Goodrich. (46). Liquid (carburetor). (47). Liquid. (48). Fundamental - air-heat (from cabin heating system) and auxiliary - liquid. (49). Martin. (50). Mercury. (51). Air-heat with use/application of heat exchangers or use of waste heat (to 1 m² it is fed/conducted by 4000 kcal/h). (52). Air-heat with use/application of gasoline heaters. (53). Fairchild C-82 "Packet". (54). Double-Wasp. (55). Lockheed "Constellation". (56). Wright cyclone 749C, 18-13 1 or Pratt-Whitney "Double-Wasp". (57). Pratt-Whitney "Double-Wasp". (58). I version - liquid; II version - thermoelectric. (59). Pratt-Whitney "Wasp Major". (60). Boeing 377 "Stratocruiser". (61). De Havilland "Comet". (62). Avon. (63). England. (64). Vickers. (65). Rolls Royce "Conway". (66). Electrothermal (glass consists of: external annealed glass, gold film, thick layer from polyvinyl butyral and fundamental power glass. (67). De Havilland DN 121 "Trident". (68). Rolls Royce "Spey". (69). Air-heat with use of hot air from compressors of engines. System is designed for the evaporation of moisture under conditions of icing to the temperature of surrounding air of equal minus 40°C. (70). Air-heat with use of hot air from compressors of engines. System works automatically and it can be included during taxiing and takeoff. (71). Vickers "Viscount". (72). Dart. (73). Thermoelectric

of cyclic action (coating "Spraymate" of firm NEPIR). (74). Thermoelectric of cyclic action (system of firm Dunlop) - air intakes. (75). Bristol - "Britain" series 310. (76). Proteus. (77). Thermoelectric of cyclic action - air intakes. (78). Vickers "Vanguard". (79). Rolls Royce or "mysteries". (80). Air-heat with use/application of heat exchangers, placed in engine nacelles. (81). Thermoelectric of cyclic action (system of firm Dunlop) - air intakes and air-heat with use of hot air from compressors of engines - input devices of engines. (82). Thermoelectric of cyclic action. (83). I version thermoelectric (glass NESA or triplex with gold film); II version - liquid. (84). Armstrong Whitworth AW 650 "Argosy". (85). Rolls Royce "Dart". (86). Thermoelectric of cyclic action (system of firm Dunlop). (87). Britain. (88). I version - mechanical of firm Goodrich; II version - air thermal. (89). I version - liquid; II version - air-heat. (90). Scottish Aviation "Twin Pioneer". (91). Olivis-Leonides. (92). I version - liquid (TKS); II version - mechanical action. (93). Exhaust system of engines is warmed by hot oil. (94). Liquid (TKS). (95). De Havilland "Dav". (96). De Havilland "Gipsy Queen" 713 PVD "Gipsy Major". (97). Avro "York". (98). Rolls Royce "Merlin". (99). Vickers VC.1 "Viking". (100). Bristol "Hercules". (101). Handley Page "Marathon". (102). De Havilland "Gipsy Queen". (103). Carburetor is warmed by hot oil. (104). Air-heat and liquid. (105). Handley Page "Hermes". (106). Bristol "Hercules". (107). Airspeed "Ambassador". (108). Bristol "Centaur".

(109). Air-heat with use/application of heaters. (110). I version - thermoelectric; II version - liquid. (111). Caravelle. (112). Rolls Royce Avon-522. (113). France. (114). Langedoc. (115). Gnome-Rhone. (116). Breguet. (117). Junkers or Humes. (118). I version - mechanical action - system kleber - Colomb; II version - Air-heat with use/application of gasoline heaters. (119). Fokker F-27 "Friendship". (120). Rolls Royce "Dart". (121). Holland. (122). I version - air-heat using waste heat; II version - mechanical action - protectors of firm Goodrich.

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The given statistical data show that widest acceptance received the air-heat de-icing system. The thermoelectric system occupies the place following it and finds ever increasing use.

The de-icing systems of mechanical and physicochemical action barely are applied on contemporary aircraft with gas turbine engines.

3. Initial data for the design of de-icing systems the design conditions of icing.

The general requirement for the deicing equipment of the aircraft, intended for the transportation of the passengers and permitted to IFR flights, can be formulated as follows: aircraft must be designed so also its de-icing system must be such that under any conditions of icing would be provided flight safety. This means that the fundamental flight characteristics, stability and aircraft handling, operation of its power plant and operation of the most important instruments must not seriously deteriorate, as were not

heavy the conditions of icing. But this does not mean that it is not allowed/assumed any ice accumulation on aircraft components. This requirement would be too heavy for a designer and is virtually unnecessary.

On contemporary aircraft from icing they must be shielded:

- the leading edges of wing and tail assembly;
- parts of the engine, ice formation on which can cause damage or upset the operation of engine (blade of intake compressor stator, strut, fairings, etc.):
- the nose/leading edge of the air intake of engine and all parts arranged/located in air intake channel, which can undergo the icing;
- cockpit windows of the pilots;
- air-pressure heads;
- all surfaces and parts, ice accretion for which and its subsequent jettisoning can cause the damage of engine and aircraft controls;

- the propellers of aircraft with the turboprop and piston engines;
- drainage branch connections and air intakes for the blowout of different instruments and aggregates/units.
- the antennas whose icing makes the work worse of radio equipment.

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All de-icing systems according to the principle of their action can be divided into two groups: the systems, antiicing (i.e. not allowing ice formations), and systems, which remove icing (i.e. dumping a periodically forming layer of ice).

It is obvious that the first group deserves in the principle of preference, however, the warning systems of icing always cannot be used for reasons of structural/design, energy or economic character. On the other hand,, as this will be shown below, the systems of the elimination of icing during the correct selection of their parameters are very effective and economical. As an example of such systems can

serve applied earlier and briefly described above, mechanical de-icing system with inflatable protectors.

For protection from the aircraft icing and its separate parts the type of antiicing system must be selected always concretely/specifically/actually, taking into account design features and possible effect of icing on aircraft performance and on the operation of its power plant. However, for example, for the protection of the cockpit windows of the pilots and pitot-static tubes must be used only the warning systems of icing. For a wing and a tail assembly usually are utilized the de-icing systems both the first and second group. For engines, as a rule, are applied the warning systems of icing with exception of those cases when it is possible to confidently experimentally demonstrate that ice formation of small sizes/dimensions on the parts of the engine and then jettisoning ice, do not exert ill effect.

But independent of the operating principle of system, it must satisfy fundamental requirement indicated above of the guarantee of safety of flights.

What specific conditions of icing must be placed as the basis of the design of the de-icing system of contemporary passenger aircraft?

This question during long time was debatable [39], [29], [35], etc. - until are accumulated sufficient statistical evidence on the water content of the supercooled clouds, according to the sizes/dimensions of cloud drops, according to the temperature of surrounding air with icing, on the horizontal and vertical extent of the zones of icing. All these data were briefly examined in the preceding/previous chapter. At present in the majority of the countries with the developed network/grid of lines and the aircraft industry officially established/installed the design conditions of the icing which differ little from each other.

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These design conditions in proportion to the storage of new data about aircraft icing in different geographic areas are periodically more precisely formulated.

Let us return to Fig. 2.2, which establishes the connection/communication of two most important parameters - water content of clouds and temperature of surrounding air.

From the examples given above it is evident that the icing can reach exceptional force. For example, in the case with aircraft "Vanguard" water content several times exceeded those values which

were given on the graph Fig. 2.2. It is possible that in nature can be encountered the more severe conditions. However, this icing is extremely rarely. To design de-icing system for such conditions obviously at present is not rational. Therefore the selection of design conditions must be produced on the base of the probability of rendezvous by the aircraft of the dangerous zones of icing [18]. It is possible to consider that into 990/o of cases of icing at appropriate temperature of surrounding air the de-icing system must reliably protect the protected parts of ice formation (or periodically remove it). In one percentage of the cases can be allowed ice formation, but this must not lead to any dangerous consequences for that time interval, during which are possible the such severe conditions of icing - to aircraft must be provided the possibility to leave the dangerous zone.

Thus, as design conditions should be accepted 990/o quantile (see Fig. 2.2), which for each temperature of air shows that in 990/o of cases the observed values of water content were less than this value, corresponding to curve.

The conditions of the icing which can be accepted for calculations, are given in Table 7.

Table 7. The design conditions of icing.

Температура окружающего воздуха (1) °C	Влажность (2) г/м ³	Средний радиус капель (3) мкм	Диапазон высот (4) м
0	0.9	8	500 9000
- 10	0.6	8	500 9000
- 20	0.4	8	500 9000
- 30	0.3	8	500 9000

Key: (1). Temperature of surrounding air. (2). Water content. (3). Mean radius of drops. (4). Altitude range.

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During the design of de-icing system must be accepted the conditions on the water contents, indicated in Table 7, at appropriate temperature of surrounding air in the range of heights/altitudes to 9000 m with an average/mean (arithmetical) radius of drops 8 μ . It should be noted that the statistical data on water content of clouds, given in Fig. 2.1 and 2.2, encompass altitude range to 5500 m. However, the separate measurements of water content, and also the immediate determination of icing intensity, accomplished at high altitudes, showed that the findings on water content must be common approximately to 8000-9000 m. Taking into account the maximum horizontal and vertical extent of zones with the values of water content indicated, it is possible with the specific

reserve to consider that for a contemporary aircraft the continuous stay of it under such conditions will not exceed 15 min (this does not indicate, of course, that the duration of less heavy icing cannot be greater).

For a comparison let us give the English design conditions of icing (Table 8 [57]). As we see, they are close to the conditions, given in table 7. However, duration of icing accepted during the tests of aircraft under these conditions, comprising 30 min, are excessively large for areas of the Soviet Union.

For the calculation of de-icing systems, and also for the evaluation of the danger of the flights of aircraft under the conditions of icing accepted the time factor plays considerable role. For example, for thermal de-icing systems serious problem is the onset of so-called "barrier" ice, which is formed beyond the limits of the warmed zone of the leading edge of wing (or tail assembly) as a result of the runoff of the settling moisture back/ago along airfoil chord. The thickness of this "barrier" ice directly depends on the time of the determination of aircraft under conditions of icing.

The recommended design conditions of icing are sufficiently rigid both for the systems of those antiicing and for the systems of

those removing icing. However, as this follows from the given graph of the quantiles of the water content (see Fig. 2.2) and as this showed the practice of flights, were possible the more severe conditions of icing.

Table 8. English design conditions of the icing of aircraft.

(1) Температура наружного воздуха °C	Водность (2) г/м³	Средний эффек- тивный диаметр капель (3) мк	Диапазон высот (4) м
0	0.8	20	9000-60000
-10	0.5	20	9000-90000
-20	0.3	20	9000-90000
-30	0.2	20	9000-90000

Key: (1). Temperature of surrounding air. (2). Water content. (3). Mean effective diameter of drops. (4). Altitude range.

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Based on this, for power plants and some instruments (connected with air-pressure head) must be provided their work under more severe conditions. In Fig. 2.2 limiting dotted curve demonstrates such conditions. However, it is necessary to consider that this curve is extrapolated, it is related to the specific geographical areas and it must be more precisely formulated subsequently in proportion to the storage of experimental data. The extent of sections with the water content, which corresponds to this curve, apparently will not exceed 5-10 km, i.e., the continuous determination of contemporary aircraft under these conditions will be approximately 1-2 min. English design conditions for power plants led to Table 9, heavier, which reflects, apparently, the special features/peculiarities of flight above the

Atlantic areas [59].

In the examination of this table it is necessary to keep in mind that at heights/altitudes less than 3000 m, the de-icing system of power plants is designed in accordance with conditions table 8. The extent of the zones of icing is established/installed following: at heights/altitudes to 9000 m of condition table 9 they operate in the sections with a length of 4.8 km (3 miles) with the breaks between them also on 4.8 km, moreover during these breaks operate conditions on table 8. At heights/altitudes from 9000 to 12200 m of condition table 9 they operate in the sections with a length of 4.8 intermittent km between them on 32 km (20 miles), moreover during these breaks the conditions of icing are absent.

The given official English design conditions of icing both for the aircraft as a whole (see Table 8) and for its power plants (see Table 9) they were developed as a result of generalizing the statistical data, assembled during long time in different geographical areas. These conditions were affirmed in 1956 by English registration control for questions of aviation.

Table 9. English design conditions of icing for the power plants of aircraft.

Температура наружного воздуха °C (1)	(2) Влажность г/м ³	Средний эффек- тивный диаметр (3) капель мкм	(4) Диапазон высот м
0	2,5	20	3000—6000
-10	2,2	20	3000—8400
-20	1,7	20	4500—9000
-30	1,0	20	4500—10700
-40	0,2	20	4500—12200

Key: (1). Temperature of outside air. (2). Water content. (3). Mean effective diameter of drops. (4). Altitude range.

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It should be noted that the common tendency in the development of the design conditions of icing consists in the gradual "weight increase" of conditions, in particular in decrease in the lower limit of temperature of surrounding air. At present in the majority of the countries de-icing systems are designed for the very low temperature of surrounding air from -30° to -40°C (comparatively recently this numeral composed in all only -20°C). The American calculated conditions of icing are close to English ones.

During the years 1956-1958 English weather service carried out

special investigations in the tropical areas of Africa and Atlantic [25], [48]. As a result of these investigations was proposed the common table of the conditions of icing, which encompasses altitude range to 18 km and is connected the liquid-water content both in the liquid state and in the form of crystals ¹.

FOOTNOTE ¹. As wire/conductor for pursuance of research served the failures of engines on aircraft "Britain" with icing in ice clouds.
ENDFOOTNOTE.

These conditions, given in Table 10, were discussed on one of the international conferences on the problem of icing; however, they were not accepted as official design conditions. It is obvious that the design of de-icing systems according to these conditions at this technological level they are irrational task. In the examination of the extent of the zones of icing in Table 10, and also 9, one should consider that the gradation of zones accepted, apparently, is to a certain extent conditional and cannot be acknowledged strict. Essential shortcoming Table 10 is also the fact that in it it is not divided "drop" and "crystal" water content.

Table 10. General conditions of drop and crystal icing.

Температура наружного воздуха (1) °C	Диапазон высот (2) м	Общее содержа- ние воды ** (3) г/м ³	Протяженность зон обледенения (4) км
0-20	3000-9 000	8,0	0,8
0-20	3000-9 000	5,0	4,8
0-20	3000-9 000	2,0	80
0-20	3000-9 000	1,0	(7) более 160
(5) От -20 до -40	4500-12 200	5,0	4,8
От -20 до -40	4500-12 200	2,0	16
От -20 до -40	4500-12 200	1,0	80
От -20 до -40	4500-12 200	0,5	(9) более 160
От -40 до -60	6000-13 700	2,0	4,8
От -40 до -60	6000-13 700	1,0	16
От -40 до -60	6000-13 700	0,25	(9) более 160
От -60 до -80	9000-18 200	1,0	4,8
От -60 до -80	9000-18 200	0,5	16
От -60 до -80	9000-18 200	0,1	(9) более 160

Key: (1). Temperature of surrounding air. (2). Altitude range. (3). General/common/total liquid-water content 2.

FOOTNOTE 2. In the general/common/total liquid-water content enters the water in the form of drops and crystals, but not in the form of vapor. ENDFOOTNOTE.

(4). Extent of zones of icing. (5). From. (6). to. (7). it is more.

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4. Determining the dimensions of the surface of aircraft shielded from icing.

The correct selection of superficial dimensions, protected from icing, has for a designer high value even at the early stage of design, since this is connected with the solution of a whole series of fundamental questions of structural/design, energy and strength character for entire aircraft as a whole.

Protection from the icing of wing (or tail assembly) must be provided on entire its spread/scope. As far as sizes/dimensions are concerned of the shielded zone along airfoil chord, then they are connected with the type of the de-icing system used. If is applied thermal anti-icing system, then the protection can be carried out by three methods: by evaporating the entire settling water during continuous intense heating, by maintaining water in the liquid state on an entire surface, which undergoes wetting, and by removing ice during periodic heating. In all three cases the area of surface (along airfoil chord) required for heating will be different; however, the minimal sizes of this surface must be logically limited by the zone of the capture/grip of the supercooled drops both for the systems, preventing icing, and for the systems of its periodic elimination.

The definition of the zone of capture/grip is produced by the

method of solution of the equations of motion of drops, which was briefly examined in chapter I. After turning anew to Fig. 1.12, in which is given the overall dependence of the relative zone of capture/grip (s/b) from parameters P and Re_0 for a symmetrical Zhukovskiy profile, let us define now affect the size of zone different factors (chord length or profile/airfoil, speed and flight altitude, angle of attack, size/dimension of drops).

Fig. 3.5 gives the graph, which characterizes the effect of the size/dimension of drops on the zone of capture/grip. As one would expect, this effect is very considerable: with an increase in the radius of drops from 10 to 30 μ the relative zone of capture/grip on lower surface grows/rises almost triply.

During the calculation of the zones of capture/grip was accepted an average/mean effective radius of drops equal to 15 μ (see Chapter I). It should be noted that in the overwhelming majority of the cases (approximately into 90%) with icing are encountered the drops in radius less than 15 μ ; however, de-icing systems must be designed for the worst conditions ¹.

FOOTNOTE ¹. The average/mean effective radius, equal to 15 μ , corresponds arithmetic mean radius of 8 μ . During calculations of the integral coefficients of settling for determining the intensity of

icing it is necessary to accept $r=3 \mu$, which is reflected under the design conditions of icing. ENDFOOTNOTE.

For the most frequently met size/dimension of drops ($r=5-7 \mu$) the zone of capture/grip composes altogether only 2-30/o of airfoil chord (at flight speed 600 km/h and chord length 4 m).

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The dependence of the relative zone of capture/grip on flight speed is given in Fig. 3.6. With an increase in the speed to 200 from 600 km/h value s/b varies from ~0.04 to 0.06.

Flight altitude, as this follows from Fig. 3.7 in the range 1000-5000 m it affects the relative zone of capture/grip to small degree. Change in altitude to 8000-10000 m leads to a more considerable increase in ratio s/b .

Fig. 3.8 gives a change in the relative zone of capture/grip with an increase in the angle of attack. With an increase in the angle of attack from 0 to 4° zone of settling on upper surface is decreased, and on lower it increases approximately doubly.

The dependence of the relative zone of capture/grip on the chord

length of profile/airfoil is given in Fig. 3.9, where for comparison is placed curve for the bent Zhukovskiy profile (at angle after all, equal to zero). As can be seen from graph, both curves are arranged/located almost equidistantly. The relative zone of capture/grip is decreased sharply with an increase in the chord length from 1 to 3 m. However, during further "elongation" of profile/airfoil ratio s/b changes insignificantly.

The given graphs show that to the zone of capture/grip most considerably affect the size/dimension of drops and angle of attack.

For the evaluation of the effect of the form of profile/airfoil (its curvature, thickness ratio, location of maximum thickness) let us examine the additionally given along other profiles/airfoils. Fig. 3.10 gives comparison for two symmetrical profiles/airfoils with identical thickness ratio (150/0), but with different values \bar{x}_c for one and the same conditions $(V_\infty = 600 \text{ km/h, } H = 5000 \text{ m, } r = 15 \text{ } \mu, \alpha = 4^\circ)$.

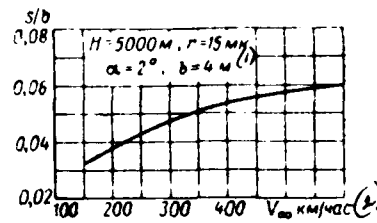
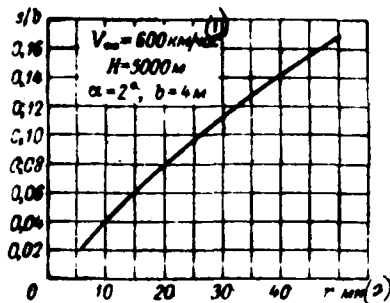


Fig. 3.6.

Fig. 3.5. Dependence of the relative zone of the capture/grip of drops s/b on a radius of drops r for lower surface of 150/o of symmetrical Zhukovskiy profile.

Key: (1). km/h. (2). μ .

Fig. 3.6. Dependence of relative zone of capture/grip of drops s/b on flight speed V_{∞} for lower surface of 150/o of symmetrical Zhukovskiy profile.

Key: (1). μ . (2). km/h.

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Profile/airfoil NACA 65₂-0.15 ($\bar{x}_c = 40\%$) has the large relative zone of capture/grip, than Zhukovskiy profile ($\bar{x}_c = 25\%$) over lower surface. With an increase in the chord length this difference is decreased.

Fig. 3.11 gives data for the lower surface of four profiles/airfoils:

symmetrical Zhukovskiy profile ($\bar{c}=15\%$, $\bar{x}_c=25\%$);

the symmetrical profile/airfoil NACA 65₂-0.15 ($\bar{c}=15\%$, $\bar{x}_c=40\%$);

curved profile NACA - 23015 ($\bar{c}=15\%$, $\bar{x}_c=30\%$);

curved profile NACA 65₁-212 ($\bar{c}=12\%$, $\bar{x}_c=40\%$).

As is evident, the relative zone of capture/grip depends substantially on the form of profile/airfoil; however, at the chord length of more than 3 m in all cases does not exceed 100/o.

Graphs in Fig. 3.10, 3.11 and 3.12 allow for profiles/airfoils, close in form, to define the zone of the capture/grip of drops with precision/accuracy sufficient for practice depending on the chord length and flight speed. The definition of the zone of capture/grip for the bodies, which essentially differ in form, must be produced by solving the differential equations of motion of drops or with experimental methods.

The calculation of the zone of capture/grip can be performed, accepting height/altitude constant ($H=5000$ m) for the values of V and angle of attack, that encompass the climb regimes, level flight and reduction/descent. In this case one should consider that for contemporary passenger aircraft the calculated case are frequently the conditions of descent and landing approach when icing can be prolonged (its cannot be avoided in practice), and engines work at light rating, which makes the operation worse of the de-icing system, which uses air from compressors.

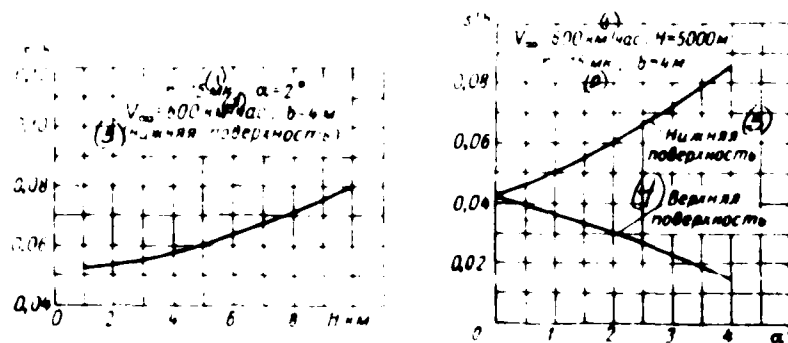


Fig. 3.7. Dependence of the relative zone of the capture/grip of drops s/l on flight altitude H for lower surface of 150% of symmetrical Zhukovskiy profile.

Key: (1). μ . (2). km/h. (3). Lower surface.

Fig. 3.8. Dependence of relative zone of capture/grip of drops s/l on angle of attack α for 150% of symmetrical Zhukovskiy profile.

Key: (1). km/h. (2). μ . (3). Lower surface. (4). Upper surface.

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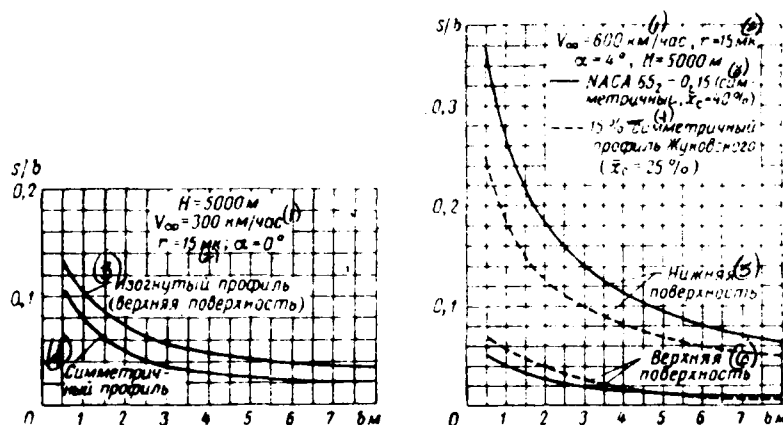


Fig. 3.9. Dependence of relative zone of capture/grip of drops s/b on airfoil chord b for 150/c symmetrical and bent Zhukovskiy profiles.

Key: (1). km/h. (2). μ . (3). curved profile/airfoil (upper surface). (4). Symmetrical profile/airfoil.

Fig. 3.10. Dependence of relative zone of capture/grip of drops s/b on airfoil chord b for symmetrical Zhukovskiy profiles and NACA 652-015.

Key: (1). km/h. (2). μ . (3). symmetric. (4). symmetrical Zhukovskiy profile. (5). Lower surface. (6). Upper surface.

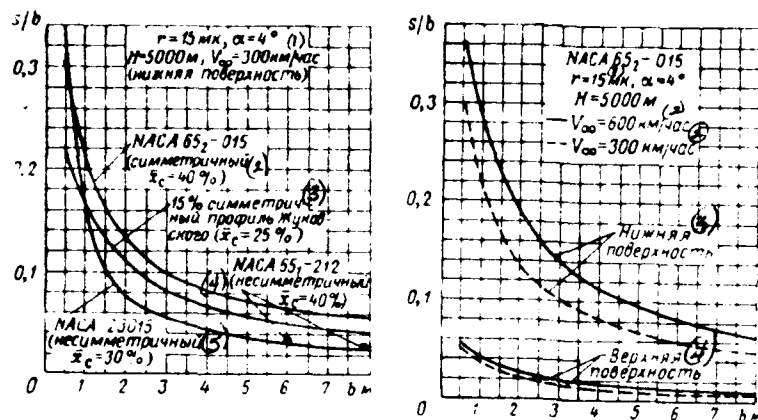


Fig. 3.11. Dependence of relative zone of capture/grip of drops s/b on airfoil chord of Zhukovskiy, NACA 65₂-015, NACA-23015 and NACA 65₁-212.

Key: (1). μ . (2). km/h. (3). lower surface. (4). Upper surface. (5). Zhukovskiy profile. (4). unsymmetrical. (5). unsymmetrical.

Fig. 3.12. Dependence of relative zone of capture/grip of drops s/b on chord length of profile/airfoil (b) for different flight speeds.

Key: (1). μ . (2). km/h. (3). lower surface. (4). Upper surface.

Let us examine the experimental data on the zones of ice

accumulation, obtained during test flights under conditions of natural icing. These data give the possibility to check the precision/accuracy of theoretical calculations and are of interest also because is considered the effect of the spread of drops, which occurs under some conditions and which is not taken into attention during calculations of the trajectories of drops. Table 11 gives the results of zone measurements of the deposit of ice over the upper surface of wing and stabilizer of the aircraft of Il-14, Il-18, Tu-104, Tu-114 (as we see the size/dimension of the cord of profile/airfoil it changed within large limits).

Measurements were conducted in level flight or reduction/descent at speeds 280-450 km/h and at the heights/altitudes less than 5000 m.

The data table 11 show that almost in 94% of cases the distribution of ice did not exceed 5.5% of airfoil chord. In 5% of cases it composed 5.5-6.5% of chord and only in all in two cases from 140 (which composes 1.43%) was observed ice accumulation in the section 8-10% airfoil chord.

Thus, experimental data, in spite of their limitedness, satisfactorily they are converged with theoretical ones.

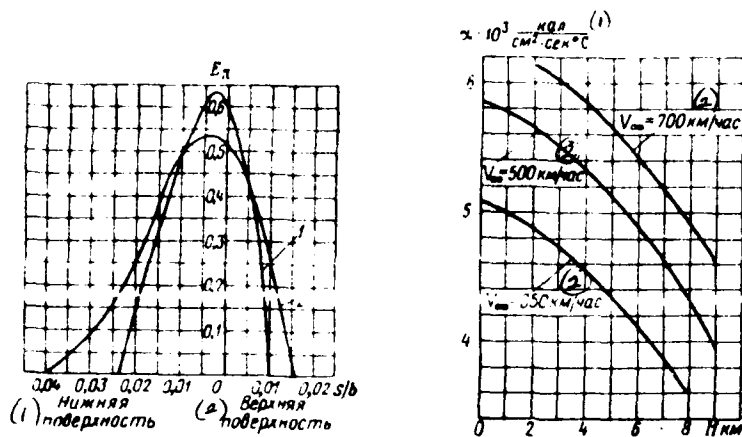


Fig. 3.13. Change in the local coefficient of settling in the duct/contour of curved profile NACA 65₁-212. ($\bar{c}_l = 40\%$, $b = 4.75$ m). 1 - $H = 3000-6000$ m, $V_{\infty} = 300$ km/h, $d_{cr,эф} = 20$ μ (mode/conditions of reduction/descent); 2 - $H = 9000$ m, $V_{\infty} = 400$ km/h, $d_{cr,эф} = 15$ μ (cruise).

Key: (1). Lower surface. (2). Upper surface.

Fig. 3.14. Dependence of heat-transfer coefficient at critical point of wing of aircraft of Tu-104 on flight altitude.

Key: (1). cal/cm²·s°C. (2). km/h.

The maximum propagation of ice over the upper wing surface

taking into account the spreading of drops, recorded on the aircraft of Il-18, did not exceed 100/o of airfoil chord (~400 mm). It should be noted that in Table 11 are connected only those cases when measurements were conducted with the aid of special attachments. The large number of observations, made by the author incidentally while conducting of the various kinds of experimental and research flights, also shows that the zone of ice accumulation, as a rule, does not exceed 5-6% chords.

In one case (on the aircraft of An-24) was observed ice formation in the very large zone on the lower surface of wing (to 25-30o/o of chord). This case was clearly connected with the spreading of the water caught into wing. Ice formation with the large width of the capture/grip on wing chord usually occurs at high temperatures of surrounding air when de-icing system comparatively easily manages the protection.

After feeding/conducting sums it is possible to draw the conclusion that the minimum value of heating surface for a wing and a tail assembly with the profiles/airfoils, used at present on passenger aircraft, must compose 8-10o/o of chord.

Besides the zone of ice accumulation to designer it is important to know icing intensity on the duct/contour of profile/airfoil, which

is characterized by the local coefficient of settling E_x . In addition to Fig. 1.11 (see Chapter I) let us examine as it changes the local coefficient of settling E_x in the duct/contour of curved profile NACA 65₁-212 with the chord, the equal to 4.75 m, which has thickness ratio 120/o and thickness distance to 400/o of chord, for the following two cases: 1) by $H=3000-6000$ m $V_{\text{нст}}=560$ km/h, mode of reduction/descent $d_{\text{ср.зф}}=20$ μ ; 2) $H=9000$ m, $V_{\text{нст}}=800$ km/h, cruise, $d_{\text{ср.зф}}=15$ μ .

Table 11. Experimental data according to 140 observations about the zone of ice accumulation on the upper surface of wing and stabilizer in o/o of chord.

(1) Зона захвата в % хорды	(2) Случаи обледенения для данной зоны захвата	(3) Количество	%
(4) До 1		70	50
(5) От 1 до 2,5		33	23,6
От 2,5 до 4,5		19	13,55
От 4,5 до 5,5		9	6,42
От 5,5 до 6,5		7	5,0
От 6,5 до 10		2	1,43

Key: (1). Zone of capture/grip into o/o of chord. (2). Cases of icing for this zone of capture/grip. (3). quantity. (4). to. (5). from.

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Fig. 3.13 gives for two cases indicated the graphs which are constructed according to the data of work [38] and are related to passenger aircraft with four engines TRD [TPJ, - turbojet engine], gross weight ~57 of t and in span of wing ~48 m. From graph evidently, the zone of capture/grip maximally reaches 40/o (over the lower wing surface in the second case).

The determination of the local coefficient of settling for

different points of profile/airfoil is the fairly complicated and labor-consuming work, which requires the solution of the differential equations of motion of drops. In the first approximation, for solving some practical tasks it is possible to recommend the following simple method.

At first is constructed graph $E_n = f(s/b)$ for value of $P = \infty$, i.e., the trajectories of drops are received as the rectilinear ones (let us recall that $E_n = \Delta h / \Delta l$, where Δh - distance between adjacent trajectories in the undisturbed region, and Δl - distance on the arc between the points of intersection of these trajectories with the duct/contour of profile/airfoil). For plotting of this dependence is traced to scale the profile/airfoil with the grid of straight paths and graphically are determined relations $\Delta h / \Delta l$ for different values of s/b (at critical point $E_n = 1$). Then is constructed the graph, analogous Fig. 1.11. After this to graph will be deposited three points for the required conditions (for concrete/specific/actual P and Re_0). The first point corresponds $E_{n \max}$ and it is determined from Fig. 1.8, in which is given the dependence of local coefficient on parameter P for a critical point. Two round points correspond $E_n = 0$, i.e. are determined the zones of capture/grip s/b by lower and upper surface. The zones of capture/grip can be defined by graph/curve (Fig. 1.12), and also on the graphs, given in present paragraph. Having three points indicated, it is possible to conduct through them

curve, following the character of that arranged/located of above the curve, constructed for value of $P=-$. As a result will be found dependence $E_{cl}=f(s/b)$ for this profile/airfoil and prescribed/assigned conditions. Thus, utilizing data regarding the local coefficient of settling at the critical point of profile/airfoil and in the zones of capture/grip, it is possible to approximately determine the distribution of local coefficient in the duct/contour of profile/airfoil.

5. Equation of heat balance.

Let us examine the equation of heat balance for the wing surface, which undergoes icing. To this question was devote the considerable number of works of the foreign (Hardy, Tribus, Messinger etc.) and Soviet (A. S. Zuyev, I. P. Mazin, R. Kh. Tenishev et al.) researchers.

In general heat transfer on the wing surface in steady process is composed from the following elements/cells:

Q_c --- the heat, selected/taken from surface as a result of the convective heat exchange.

$Q_{\text{н.в}}$ — heat, selected/taken from surface and which goes for heating of the settling on it drops of water (from ambient temperature to temperature surface):

$Q_{\text{исп}}$ — heat, selected/taken from surface as a result of evaporating the deposited on it drops of the water;

$Q_{\text{рад}}$ — heat, selected/taken from surface as a result of the radiation/emission;

$Q_{\text{т.пр}}$ — heat, selected/taken from surface as a result of the thermal conductivity of wing construction;

Q_c — heat, applied to surface as a result of compression and friction of its washing air flow (kinetic and viscous heating);

$Q_{\text{пл}}$ — heat, applied to surface as a result of the liberation of latent heat of fusion with the freezing on it of the deposited drops of the water;

$Q_{\text{ок}}$ — heat, applied to surface as a result of the transformation of kinetic energy of the drops of water into thermal with their

impact/shock about the surface;

Q_{noc} — heat, applied to surface from de-icing system.

Since is examined steady process, when on surface is established/installed certain equilibrium temperature, then the sum of all quantities of heat, applied and abstracted/removed from surface, must be equal to zero.

Let us agree to consider the heat, applied to surface, positive, and abstracted/removed from it - negative, then

$$-Q_K - Q_{н.в} - Q_{исп} - Q_{изл} - Q_{тпр} + Q_c + Q_{п.л} + Q_{эл} + Q_{noc} = 0. \quad (A)$$

In the equation given above instead of quantity of heat Q it is more expedient to examine for each term of equation the heat transfer rate q , which determines the quantities of heat, passing through a unit of surface per unit of time.

At subsonic flight speeds on the radiation heat losses it is possible to disregard, i.e., $q_{изл} \approx 0$. In the majority of the cases the heat flux, caused by thermal conductivity, also is very low in comparison with other terms of equation, since the gradients of temperature over the wing surface are usually small ($q_{тпр} \approx 0$).

Taking into account the aforesaid, we will obtain

$$-q_K - q_{н.в} - q_{исп} + q_c + q_{п.л} + q_{эл} + q_{noc} = 0. \quad (B)$$

Let us examine as it is determined each of the components/terms/addends of equation B.

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According to Newton's known formula

$$q_s = \alpha(t_s - t_\infty), \quad (3.1)$$

where α - heat-transfer coefficient in $\text{cal/cm}^2 \cdot \text{s} \cdot ^\circ\text{C}$; t_s - temperature of surface in $^\circ\text{C}$; t_∞ - temperature of the undisturbed flow in $^\circ\text{C}$

$$q_{\text{н.в.}} = m_{\text{н.в.}} c_{\text{в.}} (t_s - t_\infty), \quad (3.2)$$

where $m_{\text{н.в.}}$ - mass of the water, which settles per unit of surface per unit time, in $\text{g/cm}^2 \cdot \text{s}$; $c_{\text{в.}}$ - specific heat of water in $\text{cal/g} \cdot ^\circ\text{C}$

$$q_{\text{н.в.}} = \alpha \frac{0.628 L_{\text{н.в.}}}{c_p} \left(\frac{e_{t_s} - e_{t_\infty}}{p_\infty} \right), \quad (3.3)$$

where $L_{\text{н.в.}}$ - latent heat of vaporization in the cal/g ; $c_p = 0.24$ - specific heat of air with constant pressure in $\text{cal/g} \cdot ^\circ\text{C}$; e_{t_s} - saturating vapor pressure at temperature t_s in mb.; e_{t_∞} - saturating vapor pressure at temperature t_∞ in mb.; p_∞ - pressure-surrounding air in mb.

Formula for the heat flux, spent on the evaporation of water, is

based on analogy of the process of evaporation and convective heat exchange. In different works [12], [46], [59] are given somewhat different from each other of the expression of this formula. In this case is accepted the formula, proposed in work [12] ¹:

$$q_c = a \frac{rV_\infty^2}{2Jc_p}, \quad (3.4)$$

where r - a recovery factor (dimensionless) ²; V_∞ - speed of the undisturbed flow in cm/s; $J=4.18 \cdot 10^7$ - mechanical heat equivalent in g·cm²/s² cal.;

$$q_{m,r} = m_{m,r} L_{m,r} \quad (3.5)$$

where $L_{m,r}$ - latent heat of fusion in the cal/g

$$L_{m,r} = 79.7 \frac{\kappa a,1}{\text{cm}} \frac{(1)}{\text{mm}} \text{ } ^\circ\text{C} \quad (3.6)$$

Key: (1). with.

FOOTNOTE 1. Sometimes for larger precision/accuracy in formula (3.3) instead of values of P and $e_{t,\infty}$ are given the corresponding local importance of these values on the boundary of boundary layer.
ENDFOOTNOTE.

FOOTNOTE 2. Recovery factor characterizes the degree of the transformation of kinetic energy into thermal $\frac{t_{a,r} - t_\infty}{t_{\text{impact}} - t_\infty}$, where $t_{a,r}$ - surface temperature in the absence of heat exchange between body and

airflow: t_{air} - temperature of air if it was completely braked. In work [46] the recovery factor ϵ is taken as a constant and equal to 0.875 (as the average/mean value between 0.85 and 0.90 respectively with laminar and turbulent flow). ENDFOOTNOTE.

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It should be noted that this heat flux they frequently disregard, since the quantity of heat, which is isolated as a result of transfer of kinetic energy of drops into thermal, is considerably lower than the heat, determined by other terms of equation.

Let us examine the case when the temperature of surface is higher than zero ($t_s > 0$), which occurs in working thermal continuous de-icing system.

The equation (B) of signs the form:

$$q_{\text{noc}} = q_R + q_{\text{R.B}} + q_{\text{nen}} - q_c - q_{\text{air}} \quad (B)$$

($q_{\text{R.B}} = 0$, since freezing is absent).

After the substitution of the corresponding expressions for each term of equation, we will obtain

$$q_{\text{noc}} = \alpha(t_s - t_{\infty}) + m_n c_n (t_s - t_{\infty}) + \alpha \frac{0.628 \cdot L_{\text{nen}}}{c_p} \left(\frac{e_{t_s} - e_{t_{\infty}}}{P_{\infty}} \right) - \alpha \frac{r V_{\infty}^2}{2J c_p} m_n \frac{V_{\infty}^2}{2J} \quad (3.7)$$

Let us introduce into equation expression for the mass of the water

$$m_B = E_A W V_\infty$$

where \tilde{E} - an integral local coefficient of settling (dimensionless);
 W - water content in g/cm³.

Then

$$q_{noc} = \alpha \left[\frac{0.628 \cdot L_{ucn}}{c_p} \cdot \left(\frac{e_{tS} - e_{t\infty}}{P_\infty} \right) - \frac{rV_\infty^2}{2Jc_p} + \right. \\ \left. + (t_S - t_\infty) \right] + E_A W V_\infty c_B \left[(t_S - t_\infty) - \frac{r^2}{2Jc_B} \right]. \quad (3.8)$$

Equation (3.8) makes it possible to determine calorific requirement for protection from icing under the prescribed/assigned specific conditions when on the shielded surface settle the supercooled drops. If flight occurs in the medium, which contains ice crystals, then in equation (C) and respectively in equation (3.8) must additionally enter term q_{nc} but with opposite sign, since he will characterize the heat, selected/taken from surface for melting of the settling crystals.

The equation of heat balance for ice crystals when $t_S > 0$ takes

the form:

$$q_{noc} = q_K + q_{H.K.B} + q_{HCB} + q_{H.A} - q_{C.} - q_{D.K.} \quad (\Gamma)$$

Instead of term $q_{H.B.}$ into equation (D) enters term $q_{H.K.B.}$, which determines the heat, selected/taken from surface for heating of the settling crystals from ambient temperature to 0°C , and the heat, selected/taken for heating of the water formed after the thawing of crystals from 0°C to temperature t_s .

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Comparing equations (C) and (D), it is not difficult to see that the requirement for heat for protection from "crystal" icing is more than in the case of "drop" with the identical content per unit of volume of air, liquid water and crystals with other equal conditions.

After substituting in equation (D) the appropriate expressions for its terms, we will obtain

$$q_{noc} = \alpha(t_s - t_\infty) + m_i c_k (0 - t_\infty) + m_i c_w (t_s - 0) + \\ + \alpha \frac{0.628 L_{HCB}}{c_p} \left(\frac{t_s - t_\infty}{P_s} \right) - m_k L_{H.A} - \alpha \frac{r V_\infty^2}{2 J c_p} - m_k \frac{V_\infty^2}{2 J} \quad (3.9)$$

or

$$q_{noc} = \alpha \left[\frac{0.628 L_{HCB}}{c_p} \left(\frac{t_s - t_\infty}{P_s} \right) - \frac{r V_\infty^2}{2 J c_p} (t_s - t_\infty) \right] + \\ + \tilde{E}_d W_k V_\infty \left(c_k t_s - c_k t_\infty - L_{H.A} \frac{V_\infty^2}{2 J} \right) \quad (3.10)$$

In equations (3.9) and (3.10) m_i - the mass of the ice

crystals, which settle per unit of surface per unit time in $\text{g/cm}^2 \cdot \text{s}$

W_k — "crystal" water content in g/cm^3 ; c_k — the heat capacity of crystals (ice) ($c_k = 0.43 \text{ cal/g} \cdot ^\circ\text{C}$).

Utilizing formulas (3.8) and (3.10), let us define how changing the quantity of heat required for protection from icing in the first and in the second case with a change in the speed, flight altitude, water content and temperature of surrounding air. In this case let us consider that the deposition of crystals occurs just as drops, i.e., that the integral coefficient of settling is identical in that and in the case 1.

FOOTNOTE 1. This assumption can be accepted, since the smaller specific gravity/weight of ice crystals, in comparison with drops, is compensated by their high sizes/dimensions (see page 45).

ENDFOOTNOTE.

Calculation let us conduct for the critical point of the wing of aircraft, in the cross section where the chord is equal to 4 m. For determining the heat-transfer coefficient we will use the experimental graph, given in Fig. 3.14 2.

FOOTNOTE 2. Graph is obtained as a result of the flight experiments, carried out on the aircraft of Tu-104. ENDFOOTNOTE.

The temperature of surface let us take as equal to $+10^{\circ}\text{C}$.

The results of calculation are represented in Fig. 3.15-3.19.

As we see, with an increase in the velocity of flight the calorific requirement will increase (cm Fig. 3.15).

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However, in the case of drop icing curve $q_{\text{noc}} = f(V_{\infty})$ reaches maximum at speed ~ 600 km/h, and then requirement for heat they are decreased as a result of the amplification of kinetic heating. In the case of the crystal icing of this phenomenon it is not observed, since the supplementary heat, spent on melting of crystals (term q_{m}), exceeds the heat, which is isolated as a result of compression and friction of air flow - the requirement for heat with an increase in the speed continuously they increase. On the other hand, the graph shows that also with drop icing the quantity of heat, required for maintaining the temperature of surface, equal to $+10^{\circ}\text{C}$, composes at flight speeds 800-1000 km/h the still significant magnitude.

In Fig. 3.16 it is shown how change the individual terms of the

equation of heat balance with an increase in the speed.

Change in altitude of flight has smaller effect (Fig. 3.17). This is explained by the fact that an increase with the height/altitude of the quantity of heat, selected/taken from surface for the evaporation of water, is compensated by the decrease of heat-transfer coefficient.

The temperature of surrounding air, as this follows from Fig. 3.18, has great effect on the value of calorific requirement, moreover increase q with a temperature rise for drop icing is significantly more than for crystal. Reverse/inverse picture is observed for dependence $q=i(w)$ (Fig. 3.19). With an increase in the water content the requirement for heat in the case of drop icing grows/rises considerably less than in the case of crystal, which is connected with the effect of term q_{m0} which in the equation of heat balance for flight in water cloud is absent.

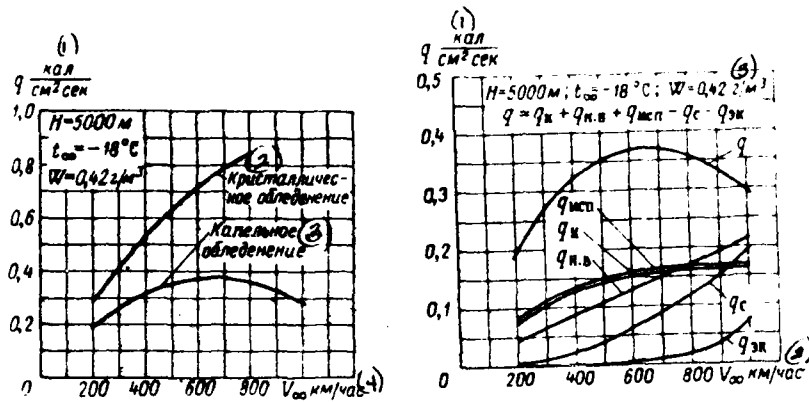


Fig. 3.15. Dependence of calorific requirement on flight speed for crystal and drop icing.

Key: (1). cal/cm² s. (2). Crystal icing. (3). Drop icing. (4). km/h.

Fig. 3.16. Dependence of heat transfer rates on flight speed for icing.

Key: (1). cal/cm² s. (2). km/h. (3). g/m³.

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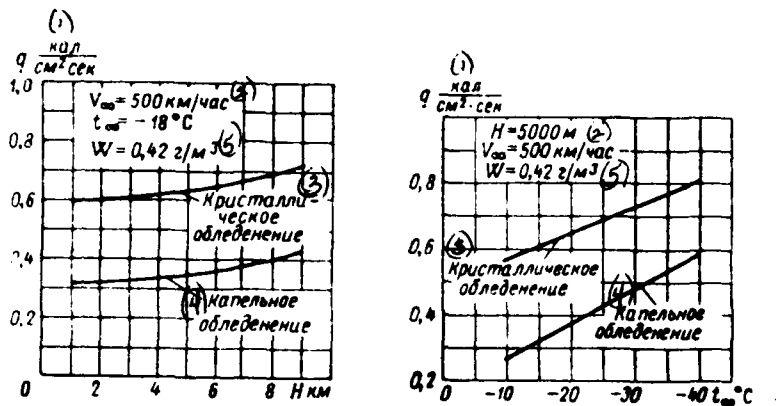


Fig. 3.17. Dependence of calorific requirement on the altitude of flight for crystal and drop icing.

Key: (1). $\text{cal/cm}^2\text{s}$. (2). км/ч . (3). Crystal icing. (4). Drop icing.

Fig. 3.18. Dependence of calorific requirement on temperature of surrounding air for crystal and drop icing.

Key: (1). $\text{cal/cm}^2\text{s}$. (2). км/ч . (3). Crystal icing. (4). Drop icing.

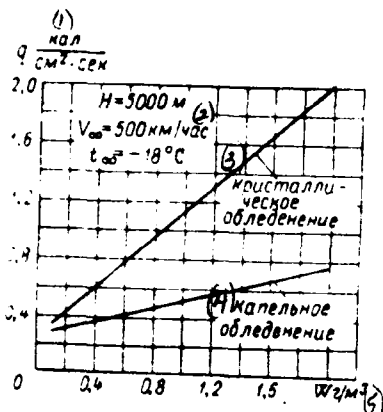


Fig. 3.19. Dependence of calorific requirement on water content of clouds for crystal and drop icing.

Key: (1). cal/cm²s. (2). км/ч. (3). Crystal icing. (4). Drop icing. (5). g/m³.

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The dependence of calorific requirement on water content and temperature of surrounding air under the design conditions of icing accepted is given in Fig. 3.20.

Graph for convenience is constructed in system of practical units. As we see, calorific requirement for the most severe conditions of drop icing ($t_x=-30^{\circ}\text{C}$, $W=0.3$ g/m³, $H=9000$ m) reach very high values of ~19000 kcal/m²·h (for the section of surface near

critical line).

For a comparison with the obtained results let us give the graph, borrowed from work [25], which shows change in dependence on the rate of necessary quantity of heat for maintaining the surface, free from ice, under conditions of drop and crystal icing. Graph is constructed for the critical point of the cylinder with a diameter of 50 mm. In the work indicated there is not the information about that, in what way constructed graph - calculation or experimental. However, the character of curves and the significant figures of values of sufficiently close to obtained are above (Fig. 3.21). It should be noted that the precision/accuracy of the calculation of calorific requirement considerably depends on the precision/accuracy of the determination of the heat-transfer coefficient α , which is the complex function of a whole series of variable/alternating [15]. For approximate computations it is possible the wing leading edge to replace by the semicylinder of the same sizes/dimensions, and the upper and lower wing surfaces to consider as the flat/plane wall, heat emission for which is determined comparatively simply. Heat-transfer coefficient depends on the state of boundary layer on the wing surface, that also always it is possible accurately to determine.

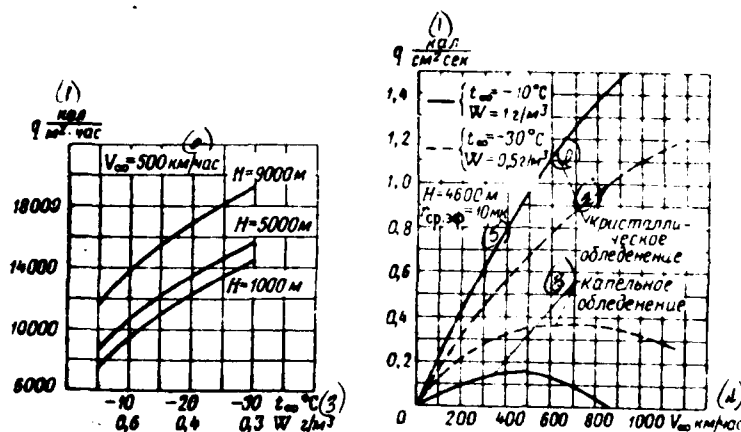


Fig. 3.20. Dependence of calorific requirement on the design conditions of drop icing.

Key: (1). cal/m²·h. (2). km/h. (3). g/m³.

Fig. 3.21. Dependence of icing required for prevention of quantity of heat on rate for leading edge of cylinder.

Key: (1). cal/cm²·s. (2). Crystal icing. (3). Drop icing. (4). km/h. (5). μ. (6). g/m³.

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The presence of water on the surface causes the shift forward of the transition point of laminar boundary layer into turbulent. For contemporary high-speed aircraft the heat-transfer coefficient

usually is determined from propagation condition for turbulent boundary layer to entire or large part of the wing surface in question.

As show investigations, great effect on heat-transfer coefficient is exerted rate and flight altitude. The temperature effect of surrounding air can be disregarded/neglected.

Besides the case examined above when $t_s > 0$, the equations given above make it possible to determine heat fluxes, also, with other two cases when the temperature of surface is negative or equal to zero. When $t_s < 0$, which is of practical use, in particular, for the de-icing systems of periodic action, it is necessary, obviously, to consider the heat, applied to surface as a result of the liberation of latent heat of fusion (when supercooled liquid settles and passes into solid state with 0°C), and the heat, given up surface by formed ice (when it is cooled to temperature t_s).

6. Thermal continuous de-icing systems.

The calculation of thermal continuous de-icing system (warming system of icing) frequently is performed to the prescribed/assigned temperature drop which is determined by the difference between the temperature of heating surface and the temperature of surrounding air

with flight in so that called "dry" air (out of clouds).

Fundamental requirement for thermal continuous system lies in the fact that to warn/prevent the icing of the shielded surface, and also not to allow the appearance of a considerable layer of ice beyond the limits of the warmed zone (so-called "barrier" ice).

Arises the question, such as is required the temperature drop in the "dry" air for preventing ice formation on the leading edge of the wing of aircraft in flight or it under the design conditions of icing.

The method of the evaluation of thermal de-icing systems according to the temperature characteristics, determined in flight out of clouds, is based on the solution of the equation of heat balance described above.

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Smallest quantity of the heat which is required for the prevention of icing, will obviously be at temperature of surface, close to zero ($t_s = +0^\circ$) ¹.

FOOTNOTE ¹. Strictly speaking, if $t_s = 0$, then in the equation of heat

balance must be introduced term q_{noc} since the freezing of liquid already occurs. ENDFOOTNOTE.

After substituting into formula (3.8) $t_s = 0$, let us have:

$$q_{\text{noc}} = a \left[\frac{0.628 L_{\text{noc}}}{c_p} \left(\frac{t_s - t_{\infty}}{P_{\infty}} \right) + \frac{r V_{\infty}^2}{2 J c_p} \right] + \tilde{E}_A W V_{\infty} c_b \left(t_s - \frac{V_{\infty}^2}{2 J c_b} \right). \quad (3.11)$$

Utilizing this expression for q_{noc} , can be determined, how, the temperature of the shielded surface in flight in "dry" air must exceed the temperature of surrounding air in order under conditions of icing to avoid ice formation.

In flight in "dry" air $q_{\text{tra}} = q_{\text{noc}} = q_{\text{ice}} = 0$ and the equation (C) takes the form

$$q_{\text{noc}} - q_k - q_c = a \left[t_s^* - \left(t_{\infty}^* + \frac{r V_{\infty}^2}{2 J c_p} \right) \right], \quad (3.12)$$

where t_s^* , t_{∞}^* - respectively the temperature of surface and the temperature of air in flight out of clouds.

By equating the first and second expression for q_{noc} , let us determine:

$$\Delta t = t_s^* - t_{\infty}^* = \frac{0.628 L_{\text{noc}}}{c_p} \left(\frac{t_s^* - t_{\infty}^*}{P_{\infty}} \right) - t_{\infty}^* + \frac{\tilde{E}_A W V_{\infty} c_b}{a} \left(t_{\infty}^* - \frac{V_{\infty}^2}{2 J c_b} \right). \quad (3.13)$$

Thus, the required temperature drop in "dry" air Δt depends on the series/row of the parameters, into which enter the temperature of air under conditions of icing, water content, flight speed, geometric characteristics of the shielded profile/airfoil and size/dimension of drops (determined by value E), etc.

Introducing in equation (3.13) design conditions according to water content and temperature, it is possible to obtain for each concrete/specific/actual profile/airfoil the required temperature drop to which must correspond the temperature drop, determined during tests in "dry" air.

Formula (3.13) was subjected to the experimental check which showed the completely satisfactory convergence of theoretical and experimental data.

Let us give two examples of this checking.

1. Determination in "dry" air of temperature drop at critical points of nose/leading edge of air intake of aircraft of Tu-134 at height/altitude of 4000 m and indicated airspeeds 400 km/h showed that datum composes 32-33°C (measurements were conducted during tests of one of versions of experimental de-icing system).

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During the incidence/impingement of aircraft at the same height/altitude and speed under conditions of icing at temperature of surrounding air of -20°C and average/mean water content 0.2 g/m^3 occurred ice accumulation all over circumference of air intake, in spite of the previously connected de-icing system. Calculation according to formula (3.15)¹ for these conditions showed that the required temperature drop for the prevention of icing had to comprise not less than 39°C (instead of $32-33^{\circ}\text{C}$).

FOOTNOTE 1. Heat-transfer coefficient at the critical point of the wing of the aircraft of Tu-104 was determined experimentally.

ENDFOOTNOTE.

2. Temperature drop near critical point in one section of wing of aircraft of Tu-104 composed 25°C in "dry" air at height/altitude of 2000 m and indicated airspeeds 400 km/h.

With accomplishing of flight in the zone of icing in the section

of wing indicated occurred ice formation. Flight conditions were following: $H=2000-3000$ m, $t_a = -11^\circ\text{C}$, $V_m=400$ km/h, $W_{cp}=1.0$ g/m³, de-icing system was connected prior to the entry into the zone of icing.

Calculation according to formula (3.13) for these conditions showed that the required temperature drop must be not less than 33°C . This was the confirmed further experiment when engine power rating was transferred into this, during which appropriate temperature drop in "dry" air it composed $39-40^\circ\text{C}$; in this section of wing was begun the thawing of ice, and then it was distant completely. (Complete removal of ice it occurred already on leaving of aircraft from cloudiness).

Fig. 3.22 gives the dependence of ice formation required for prevention of temperature drop on the design conditions of icing. Calculation is carried out for the leading wing edge of the aircraft of Tu-104. As can be seen from graph, the proposed previously required temperature drop in 35°C provides protection from icing under design conditions only to -15°C .

The analysis of formula (3.13) at different possible values of the entering it values showed that the required temperature drop for at present aviation profiles/airrolls used must comprise in the earth/ground not less than 50°C .

A change in the required temperature drops in heights/altitudes is shown in Fig. 3.23.

Continuous de-icing system must prevent ice formation not only on the warmed part of the surface, but also beyond its limits, which is reached by the selection of the sizes/dimensions of the shielded zone and by the maintenance of the corresponding temperatures of surface.

The graphs/curves given in the preceding/previous paragraph illustrated the requirements for heat for maintaining the temperature of the surface, equal to $+10^{\circ}\text{C}$.

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However, the achievement of this temperature does not in any way mean that the water, which settles on wing, will completely evaporate and will not occur its runoff beyond the limits of the warmed zone.

Actually/really, for continuous de-icing systems the problem of the formation of barrier ice has serious value. Experiment shows that accomplishing endurance flight under conditions of intense icing leads to the appearance of barrier ice even in de-icing systems with

sufficiently high temperature drops. If the settling water completely does not evaporate in the zone of settling, its remainder/residue leaks off back/ago (on upper and lower surface of wing) in the form of the separate streams which then freeze and are formed uneven ice built-up edges at considerable distance from leading edge. Sometimes these ice built-up edges take the form of separate flows (Fig. 3.24), while sometimes - continuous ice barrier (Fig. 3.25). ⁴ The formations of barrier ice it would be possible to avoid, after ensuring on an entire wing surface the temperature, exceeding 0°C; however, the structural/design and energy difficulties of this method they were obvious.

Another method, which removes the possibility of the onset of barrier ice, it consists in the evaporation of entire water over the area of its settling. This would make it possible to have minimum zone heating along chord (corresponding to the zone of capture/grip), but it would require to ensure too high a temperature in the small section of surface, which also presents considerable difficulties.

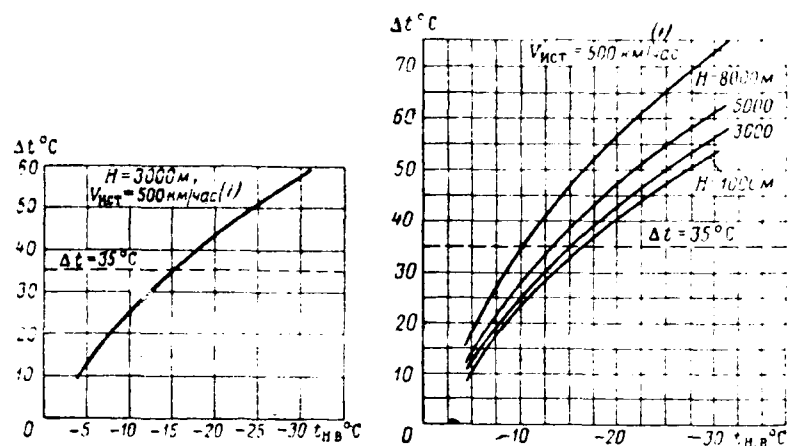


Fig. 3.22. Dependence of ice formation required for prevention of temperature drop on the design conditions of icing for the leading wing edge of the aircraft of Tu-104. Key: (1). km/h.

Fig. 3.23. Dependence of required in "dry" air temperature drops from computed values of temperature of surrounding air and water content for different heights/altitudes.

Key: (1). kg/h.

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As illustration let us give graph (Fig. 3.26) borrowed from work [38] which shows the dependence of calorific requirement for the

complete evaporation of water over the area of its settling from water content and temperature of surrounding air. As is evident, for the de-icing system, based on the principle of the evaporation of the drops of water over the area of their settling, the calorific requirement, per unit of the wingspan, depends in essence on the value of water content. The temperature effect of surrounding air is small.

Thus, the total quantity of heat, which requires for the prevention of icing, depends on selected safety method.

If de-icing system is projected/designed then so as to ensure the evaporation of water over area larger than area of settling the drops (which usually and occurs), then calorific requirement depends both on the temperature of surface and on the size/dimension of the warmed zone. Fig. 3.27 gives that undertaken from the same work of graphs/curves, that shows a change in the heat required for evaporating a quantity in dependence on the warmed zone in chord and on the temperature of the surface (temperature for this warmed zone is accepted by constant).



Fig. 3.24. Barrier ice flows on the upper surface of stabilizer after flight under conditions of icing.

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From graph it is evident that, for example, for the heating 150/o chord at temperature of surface of 24°C it is required by 16000 kcal/h•m, and for the heating 420/o chord at temperature of surface of 12°C it is required by 23300 kcal/h•m.

Graph clearly illustrates, which during the guarantee of high

temperature of surface and smallest warmed zone is required less than the heat.

Of that examined it is above evident that continuous de-icing systems (systems, antiicing) received widest use on contemporary aircraft. In the majority of the cases - these are the air-heat systems. However, the large requirements for heat which grow/rise with an increase in the sizes/dimensions of aircraft, their speed, flight altitude caused considerable difficulties because of the need for the selection too or great a quantity of air from engines. This it forced to turn to the systems of the periodic action whose requirements for energy are considerably less.

Before passing to the second group of systems, are given several short descriptions of typical air-heat continuous systems.

To the aircraft of Tu-104 the protection from the icing of wing and power plants is accomplished/realized with the aid of the hot air, selected/taken from the compressors of engines.

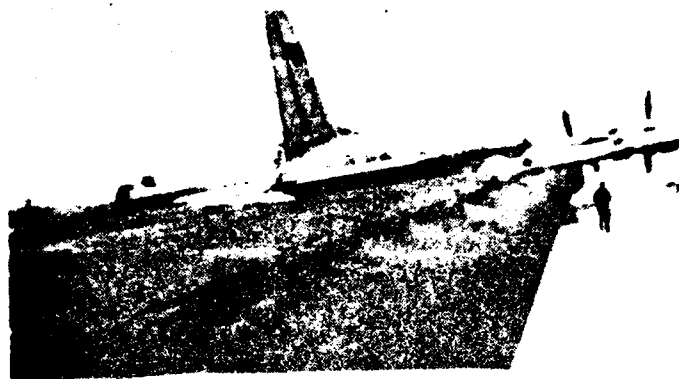


Fig. 3.25. Continuous barrier ice on the upper surface of stabilizer after flight under conditions of icing.

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The schematic diagram of de-icing system is shown in Fig. 3.28. The air, gathered/taken in the eighth compressor stage (with the temperature, which reaches by 240°C), on conduit/manifold 1 through locking 3 and reverse/inverse 4 valves enters the right and left wing leading edges. System has a conduit/manifold of cross-feed by 2, through which is provided the air supply in the failure of one of the engines. In this case the corresponding check valve prevents the leakage of hot air to the side of failed engine.

The temperature of the air, which enters leading edge of wing,

in dependence on engine power rating and temperature of surrounding air oscillates from 70 to 200°C.

The deicer of the wing leading edge is arranged as follows (Fig. 3.29). To skin/sheathing 1, made from Duralumin in thickness 1, 2 mm, from inside is riveted corrugation 2, prepared also from Duralumin in thickness from 0.6 to 1 mm. The corrugation of split, consists of the upper and lower panels which during installation form ten-millimeter slot along the leading edge of wing.

Along leading edge is established/installed dead/blind arm 3, which is wall from Duralumin with a thickness of 1 mm which is fastened to corrugation. Wall from the side of forechamber is coated by fiberglass laminate. Arm divides leading edge into two chambers/cameras: front/leading A and rear B, which communicate through the channels of corrugation.

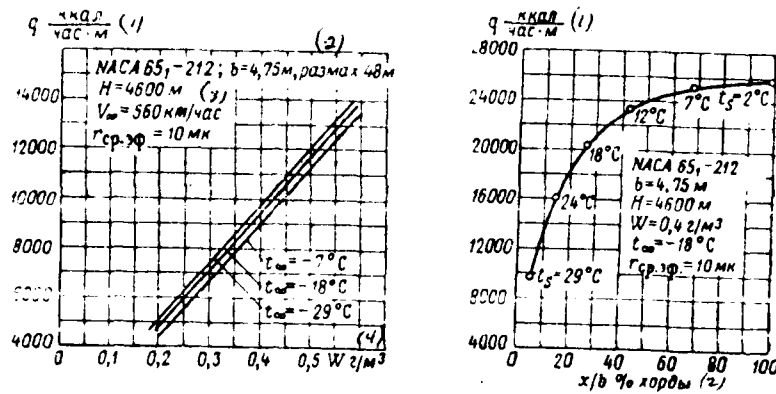


Fig. 3.26. Dependence of calorific requirement for the complete evaporation of water on water content and temperature of surrounding air.

Key: (1). kcal/h·m. (2). spread/scope. (3). km/h. (4). g/m.

Fig. 3.27. Dependence of quantity of heat q required for evaporation on size/dimension of warmed zone along airfoil chord x/b and on temperature of surface t_s .

Key: (1). kcal/h·m. (2). chord.

The channels of corrugation are arranged/located along wing

profile and have variable/alternating cross section. The height/altitude of corrugation comprises at leading edge 4-5 mm, in area of arm - 6-8 mm and in trailing profiles/airfoils 4-2-3 mm.

The internal part of forechamber is coated by the fiberglass laminate with a thickness of 0.5 mm, which is shield 5, which are guided the hot air through the slot in arm to the leading edge of wing.

The warmed zone of wing occupies 14-15% of chord. Hot air is supplied into forechamber A, is distributed along the channels of corrugation it washes wing skin from its inside. Further air enters rear chamber/camera B, whence it is rejected in the atmosphere through special openings/apertures in wingtip fairings.

The end sections of wing, which have smaller absolute sizes/dimensions and subjected therefore to more intense icing, have the intensive heating due to the special shaping of the channels of corrugation.

The start of the de-icing system of wing is produced with the aid of the tap/crane of control 5 (see Fig. 3.28) pneumatic action¹, the co-pilot established/installed on instrument panel.

FOOTNOTE 1. On the aircraft of Tu-124, which has the analogous construction/design of the de-icing system of wing, control of tap/crane - electrical. ENDFOOTNOTE.

Control/check of the operation of system is accomplished/realized by the thermocouples whose sensors are established/installed in conduits/manifolds at the leading edge entry, and by the manometer, which measures the pressure in the control system.

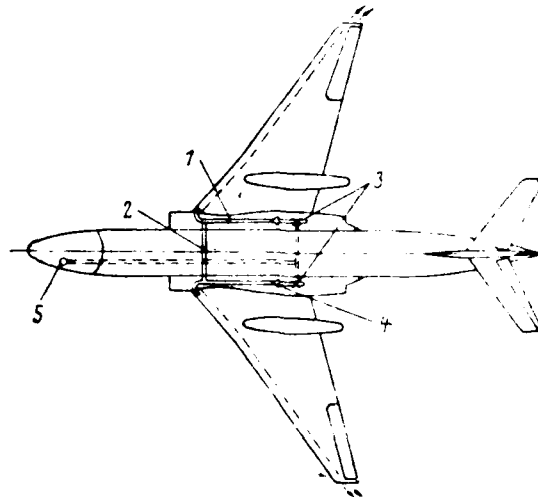


Fig. 3.28. Schematic diagram of the de-icing system of the wing of the aircraft of Tu-104.

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The expenditure of air for the de-icing system of wing composes 9200 kg/h at the height/altitude of 1000 m and it falls to 5600 kg/h at the height/altitude of 7000 m (in level flight with a speed of $V_{mp} = 400$ km/h).

For de-icing system of such type is characteristic the dependence of the effectiveness of its action on engine power rating. This makes it possible in known limits to enforce the heating of the

shielded surfaces by an increase in engine power rating. So, the increase in the operating mode, which corresponds to an increase in the level flight of speed from 400 to 600 km/h in instrument, leads to the increase of the expenditure of air for wing on 700 kg/h. The temperature drops on heating surface in this case considerably grow/rise: on 13-15°C at the critical points of the wing leading edge and on 10-12°C - on the lateral surface of nose/leading edge. Curve in Fig. 3.30 illustrates the dependence of the temperature drop on the leading edge of the wing leading edge on flight speed in the connected de-icing system.

On the other hand, if we ensure the necessary temperature drops in low engine power ratings, then in the increased modes/conditions they will be unjustifiably high, which requires the regulation of the quantity of air, which enters the deicers.

The de-icing system of the aircraft of An-24 also air-heat, with the use of hot air, abstracted/removed from the compressors of engines.

The schematic diagram of de-icing system is shown in Fig. 3.31.

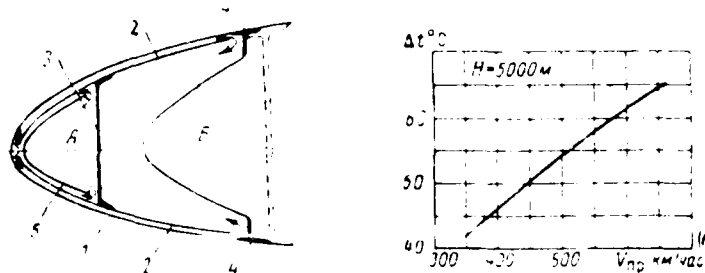


Fig. 3.29. Schematic of the heating of the leading edge of the wing of the aircraft of Tu-104.

Fig. 3.30. Dependence of temperature drop Δt on leading wing edge of aircraft of Tu-104 on flight speed V_{np} .

Key: (1) . km/h.

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The air, selected/taken from the tenth compressor stage of the engines through special collars, comes under pressure to check valves 1, controlled by the electrical mechanisms which are included by the toggle switch, arranged/located on special control panel in the co-pilot.

Control/check of full gate of the taps/cranes of air supply is

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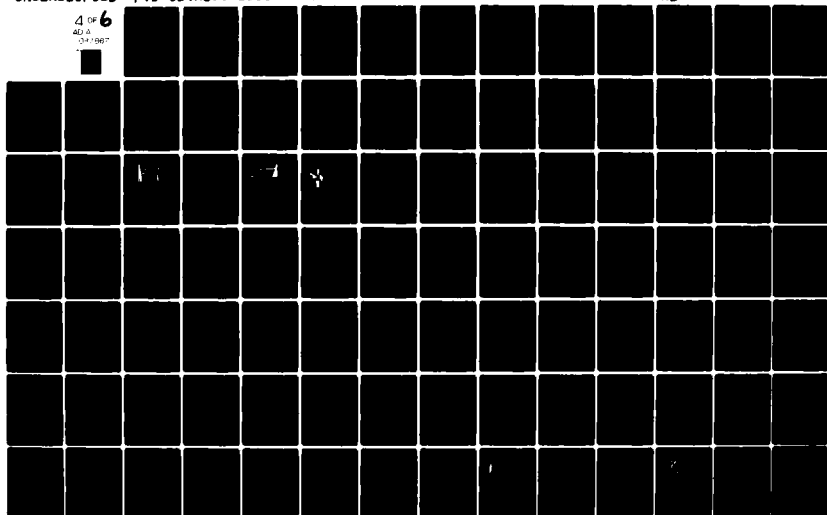
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accomplished/realized on the firing of two bulbs, arranged/located on the same panel. From stop cocks the air proceeds to the maneuvering valves of pressures by 2, which maintain the pressure in system, equal to 3.2 ± 0.2 atm (tech). Further through check valves 3 air heads toward the deicers of wing and tail assembly.

On the aircraft of An-24 for supplying hot air to heating surfaces it is applied ejection in contrast to the aircraft of Tu-104 with direct air supply from the compressors of engines. The de-icing system of wing, tail assembly and air intakes of engines structurally/constructurally differs from the usual schematic of the air-heat system, used on many aircraft types.

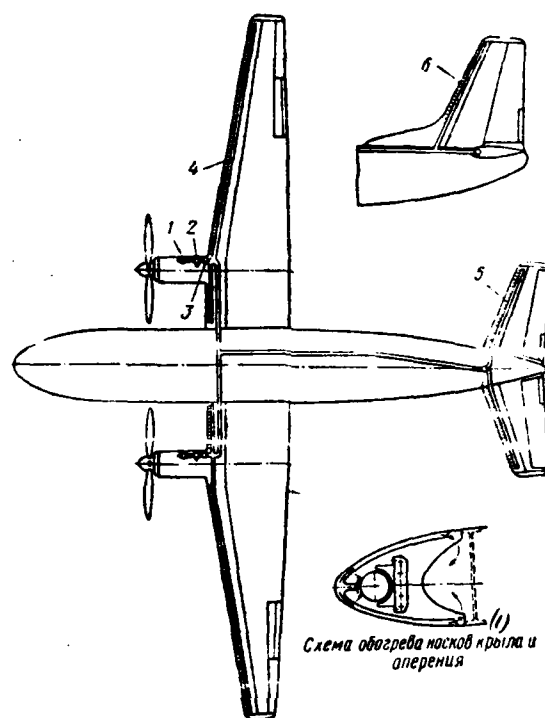


Fig. 3.31. Schematic diagram of the de-icing system of wing and tail assembly of the aircraft of An-24. 1 - check valves, 2 - pressure regulators, 3 - check valves, 4 - deicer of wing, 5 - deicer of stabilizer, 6 - deicer of fin.

Key: (1). Diagram of the heating of the leading edges of wing and empennage.

On aircraft Ap-24 is used the so-called micro-ejector anti-icing system, made as follows.

Along the shielded surface of noses/leading edges is laid the conduit/manifold made of the stainless steel with a diameter of 45 mm with the micro-nozzles with a diameter of 0.8 mm on wing and 1.0 mm on fuller's earth and stabilizer.

The receiver of deicers in complex with the micro-nozzles whose space is equal to 15 mm, forms the system of the micro-ejectors, which work according to recirculating method. The diagram of air circulation in the leading edges of wing and tail assembly is shown in Fig. 3.31. Hot air from the conduit/manifold through micro-nozzles is supplied directly to the leading edge of the protected surfaces and along the channels, formed by skin/sheathing and corrugation with constant section along chord, enters further into the rear chamber/camera of nose/leading edge. The part of exhaust air will be ejected by micro-ejectors and anew it enters the corrugations of deicers. Exhaust air moves over the channel, formed by skin/sheathing of deicer and by front/leading longeron/spar, and through openings/apertures in ending it is rejected in the atmosphere.

The warmed zone of noses/leading edges composes 100/o of chord for a stabilizer and a fin and 11-150/o of chord for a wing.

The flow rate of air, which enters the de-icing system of wing and tail assembly, in the range of heights/altitudes from 1000 to 6000 m composes respectively 2800-1800 kg/h.

The advantage of micro-ejector system is the considerable decrease of the air flow rates from engine in comparison with de-icing system with usual ejectors.

Thus, for instance, flow of air to the stabilizer of the aircraft of An-24 with micro-ejector system approximately/exemplarily to 30o/o is lower than the expenditure for the same stabilizer with usual ejectors.

It is known that during the use/application of ejectors in deicer the air flow rate is determined, in essence, by the flow rate through the ejector and to low degree it depends on engine power rating. This is advantage of such type of system in comparison with de-icing system with direct air bleed from compressor.

De-icing systems with the use of ejectors for air supply are applied on Soviet aircraft with the turboprop engines (An-10, An-24), the selection of a large quantity of air from which is impossible

without a considerable reduction/descent in the power. It should be noted that the mode/conditions of the operation of the turboprop engines, which have permanent revolutions, virtually little affects the effectiveness of the action of de-icing system.

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In the series/row of foreign aircraft with TVD a question of hot-air heating of the surfaces shielded from icing is solved with the aid of the installation of the heat exchangers, in which the air, gathered/taken from the atmosphere, is heated due to waste heat of engine.

An example of the use/application of this system are aircraft "Argosy", "Vanguard" and "Viscount."

On aircraft "Argosy" by warm air are warmed the wing leading edges. The air, entering into heat exchangers from the atmosphere through special air intakes, is heated by waste heat and heads then for distributing pipe (Fig. 3.32 and 3.33). It the air enters the fundamental channel of nose/leading edge, formed by the lower covering and the fiberglass laminate partition/baffle, arranged/located along the length nose/leading edge.

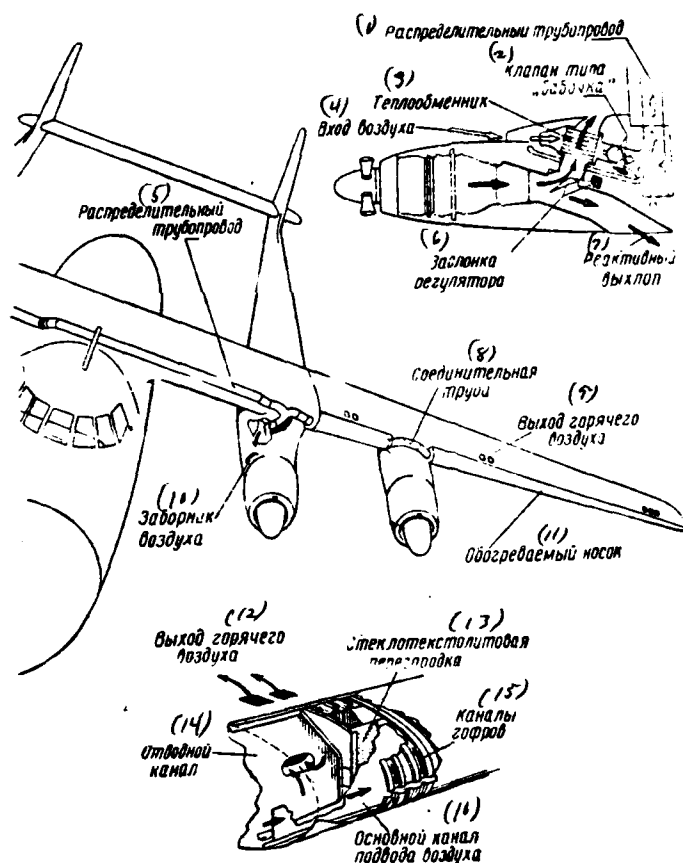


Fig. 3.32. Schematic diagram of the de-icing system of aircraft "Argosy".

Key: (1). Distributing pipe. (2). Valve of type "butterfly". (3). Heat exchanger. (4). entry of air. (5). Distributing pipe. (6). Shutter/valve of regulator. (7). Reactive/jet exhaust. (8). Union pipe. (9). yield of hot air. (10). Air intake. (11). Warmed

nose/leading edge. (12). yield of hot air. (13). Fiberglass laminate partition/baffle. (14). Branch/drain channel. (15). Channels of corrugations. (16). Fundamental channel of supply of air.

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Further the air through the slot in the lower covering, made in the form of corrugations, enters the channels of corrugations, washing the wing leading edge. Then air leaves corrugations and is collected/built in the chamber/camera, formed by spar web and by fiberglass laminate partition/baffle, after which it is rejected in the atmosphere on special diverters and openings/apertures in the upper part of the wing.

Heat exchangers are arranged/located on internal engine nacelles from inside. The supply of cold air and exhaust gases to heat exchanger is regulated by two shutters/valves and is arranged in such a way that the shutter/valve of the air intake of exhaust gases cannot be opened/disclosed as long as will not be completely opened the shutter/valve of the air intake, which enters from the atmosphere.

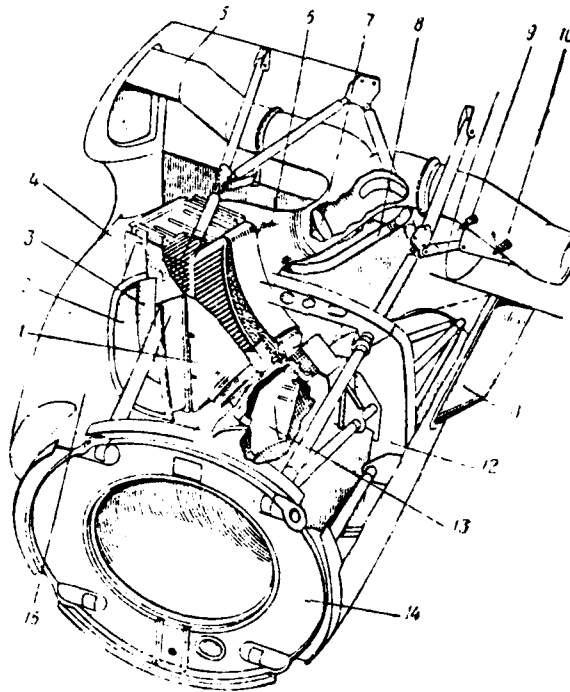


Fig. 3.33. Layout of the heat exchangers of de-icing system (on internal power plants). 1 - channel of hot gases, 2 - air intake of heat exchanger, 3 - heat exchanger, 4 - exhaust tube of hot gases, 5 - manifold, 6 - channel of hot air, 7 - valve of the type "butterfly", 8 - tube for air bleed for the heating of the air intake of heat exchanger, 9 - thermosensitive elements, 10 - mercury thermorelay, 11 - exhaust duct, 12 - power frame, 13 - shutter/valve of exhaust duct, 14 - fire wall, 15 - jacket.

The position of the shutter/valve of the air intake of exhaust gases automatically is regulated depending on the temperature of hot air (signaling is accomplished/realized with the aid of the fire detectors, arranged/located on manifold) so that with an increase in the temperature of air in tube is supplied signal to the closure of shutter/valve, and with decrease - to its complete opening. The oscillations/vibrations of the mechanism of control of shutter/valve are damped.

In system is provided for the signaling about superheating - with an increase in the temperature of air in tube to 190°C operates/wears mercury switch, which closes the relay circuit of signaling.

Besides the tube of signaling about superheating on left ceiling flap are mounted two temperature indicators of air in tube, calibrated from +50 to +200°C.

For preventing the possibility of the start of deicer on the earth/ground, which can lead to superheating of construction/design, control of the mechanism of the opening of the shutter/valve of exhaust gases is interlocked with the reduction of landing gear

struts. ^Q Flow rate of hot air through each heat exchanger (i.e. to one half wing) - about 3600 kg/h. Temperature drop on the leading edge of center section (in the place of the supply of hot air) reaches 100°C, on lateral surface of 50°C; in outer wing panel temperature drops they comprise: by 50°C on leading edge and 35-40°C on lateral surface.

The de-icing system of the wing of aircraft "Vicount" and "Vanguard" - is air-heat. Air due to velocity head enters the heat exchangers where it is heated by the exhaust gases, selected/taken after turbine in a quantity of approximately 20/o, and further heads for the channel, arranged/located along wing. From channel the air enters the wing leading edge, it is collected/built in offtake and is rejected in the atmosphere through openings/apertures in wing tip.

Temperature of exhaust gases at the entry into heat exchanger of 500°C. Air in heat exchanger is heated to 165°C and is cooled in wing to 70°C.

Heat exchangers are arranged/located in internal engine nacelles and are made from tubes made of the heatproof steel with a diameter of 4-4.5 mm. Tubes are arranged/located vertically; air moves within them from bottom to top. Exhaust gas washes tubes horizontally.

For cessation the air supplies in the upper part of the heat exchanger are by louver.

For the protection of the turbojet aircraft VC-10 from icing is utilized hot air from the compressors of engines.

Air bleed on each engine is accomplished/realized from the latter/last compressor stages of the high and low pressure (see Fig. 3.34). The feed systems of air from each pair of engines together with their aggregates/units of automatic regulation function separately from each other.

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The air, selected/taken from the compressors of the high and low pressure of each pair of engines, mixes and, passing through reduction and check valves, it falls into general/common/total distributing pipe, which passes in fuselage. Thus, because of cross-feed during the malfunction of one or two engines air supply is provided by other two engines.

After the branching off of conduit/manifold in fuselage (point of cross-feed) the conduit/manifold is passed on center section and further into root of the wing where the air is utilized for the drive

of turbine of cooling evaporative installation.

To the wing leading edge the air is supplied through check valves. To slats the air enters from the wing leading edge through the telescopic joint and it passes on conduit/manifold along the spread/scope of slat. Through openings/apertures in conduit/manifold the air falls at first into intermediate collector/receptacle, and from the latter - through slots into space formed by external and lower coverings (Fig. 3.35). As derived/concluded air into the fixed wing leading edge after slat. With the extended slats the exhaust air emerges through special openings/apertures. These openings/apertures coincide with openings/apertures in the fixed wing leading edge with the retracted slats. In this case the exhaust air from slats is removed together with air from the fixed wing leading edge. When slats are released, openings/apertures in the upper surface of the fixed wing leading edge are closed by trip valves.

The section of leading edge of wing in long approximately three meters in fuselage (i.e. in the zone of the location of engines) has the intensive heating for the preservation of engines from the incidence/impingement of the pieces of ice which can be formed and fly in the case of the insufficient effectiveness of the heating of wing in this section. For aircraft VC-10 this is especially important, since its engines Rolls Royce Conway have duralumin

rotating compressor blades. The intensive heating is provided due to the elevated temperature of air entry for which is arranged/located on fuselage.

The zone heating of wing in the percentages of chord varies from 100% in root, to 140% - at tip of the wing (over upper surface).

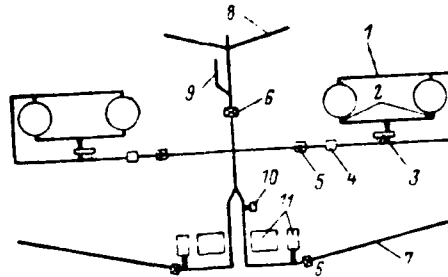


Fig. 3.34. Schematic diagram of the de-icing system of aircraft VC-10. 1 - pipe of air bleed from low-pressure compressor, 2 - air extraction manifold from high-pressure compressor, 3 - thermal valves, 4 - reduction valves, 5 - main check valves, 6 - check valves, 7 - deicer of wing, 8 - deicer of stabilizer and fairing about the stabilizer, 9 - deicer of fin, 10 - branch of engine starting, 11 - evaporative installation.

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Air supply to the heating of the tail assembly from fundamental conduit/manifold is accomplished/realized through the two-position check valve.

In the case of damaging to electrical control circuit the valve remains in position "opened".

Air, passing through the check valve, proceeds to the nose/leading edge of fin, stabilizer, and also to fairing (butt joint of stabilizer with the fin) whose lateral surfaces to avoid the wedging of rotary stabilizer with icing are warmed.

Air for the heating of fairing enters from the coarse-wire/coarse-conductor of the stabilizer through the tee. In connection with the fact that the stabilizer in flight is deflected, into conduits/manifolds are introduced flexible sections.

Air in the noses/leading edges of fin, stabilizer and fairing moves over the channels, formed by dual skin/sheathing, and it is derived/concluded in the atmosphere through the grids/cascades which are arranged/located on the lateral surfaces of the upper part of the fin.

The conduits/manifolds, arranged/located within nacelles and fuselage, are made made of the stainless steel with double walls. Upon the decomposition of internal wall, external will avoid the incidence/impingement of air into fuselage.

In all points of connections, closed in the event of damage by jacket, are established/installed expansion bellows.

The conduits/manifolds of the tail assembly are also made from the stainless steel with flexible expansion bellows. Exception is flexible conduit, established/installed on rotary stabilizer.

The conduits/manifolds, arranged/located in wing, are made from aluminum alloy with exception of channel in the telescopic joint, which makes it possible to be moved for slat.

Temperature of air in distributing pipe of 225°C , pressure of 3.5 kg/cm^2 . This temperature is maintained by the feed control of air from high-pressure compressor: with a temperature decrease thermal valve closes with compressed air check low-pressure valve. After this into system comes the air only from high-pressure compressor.

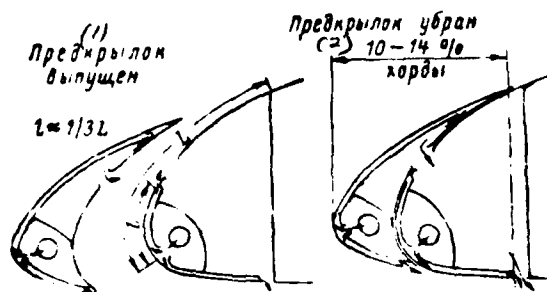


Fig. 3.35. Schematic of the heating of the leading edge of wing and slat of aircraft VC-10.

Key: (1). Slat is released. (2). Slat is retracted by 10-14o/o of chord.

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The expenditure of air for entire de-icing system is approximately 26000 kg/h, from them: to wing - about 14500 kg/h, to stabilizer - 5500 kg/h, to fin - about 2000 kg/h and to engines - 4000 kg/h.

When is not required heating, by overlapping high-pressure valve is established/installed in position "air it is openly" and utilized only for actuating of the turbine of cooling evaporative installation.

In the failure of engine check valves prevent air losses to the side of failed engine or pair of engines.

During engine starting on the earth/ground air flow moves in opposite direction. Therefore thermal valves, reduction valves and main check valves are established/installed in position "opened".

For a signaling about superheating before main check valves in engine nacelles and in distributing pipe of fuselage are established/installed the thermocouples. On flight engineer's panel are tubes of signaling about superheating, and also temperature indicator of air in conduit/manifold.

Is provided for also the signaling of air pressure in the conduits/manifolds: in the air duct it is established/installed two pressure sensors, connected to one indicator lamp on flight engineer's panel.

The de-icing system of aircraft VC-10 is designed in such a way as to provide protection from icing to the temperature of surrounding air of -30°C and height/altitude on the order of 10000 m.

At international conference on the protection of aircraft and

helicopters from icing, which passed to 1961 in England, the firm Blackburn proposed the design of new de-icing system, which was based on heating the shielded surface by the thin film of the warm air, selected/taken from engine [55]. The warm air through narrow slots in the leading edge of wing and tail assembly is blown out with the transonic speed to the external surface of the shielded aircraft components and heats it. Besides protection from the icing this method can be used also for boundary layer control for purpose of an increase in the lift and decrease of drag.

The schematic diagram of the combined boundary layer control system and warning/prevention of icing is shown in Fig. 3.36 and 3.37.

Air is selected/taken from the compressor of each engine and is supplied through two parallel pipes to general/common/total air duct. The maximum quantity of air, required for warning/preventing the icing, is approximately 5.50/o of general/common/total air flow rate. For boundary layer control it is required by 120/o.

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In the case of failure of one of the engines the necessary air flow rate is provided by one operating engine, since failed engine

automatically is insulated from high-pressure circuit by check valve. In this case the effectiveness of system does not deteriorate, since entire the necessary quantity of air can be obtained from each engine.

Air supply from common duct into the conduits/manifolds of leading edges and to slots is regulated separately by decreasing the pressure, also, with the aid of changeover valves.

For the functional test of system on the earth/ground in the end sections of the leading edges of wing and stabilizer are established/installed the manometers. In air the system is included by hand during the operation of signal indicator icing.

Pressure and temperature of air for boundary layer control are 11.25 kgf/cm² with 225°C and 7.6 kgf/cm² with 345°C. For the needs of de-icing system the pressure is decreased to 1.75-2.45 kgf/cm² at the same temperatures. Conduits/manifolds are made made of sheet steel by welding.

Slots in the leading edges of wing and stabilizer have a size/dimension of 0.635 mm on upper surface and 0.178 mm on lower surface. Are arranged/located slots at a distance with 1-50/o of chord from leading edge.

The surface of nose/leading edge in front of slot can be shielded with the aid of convective system during the use of a cavity of nose/leading edge near leading edge as air duct.

It is assumed that because of large air speed, which takes place through the slot, the water, which leaks off back/ago, will be blown away.

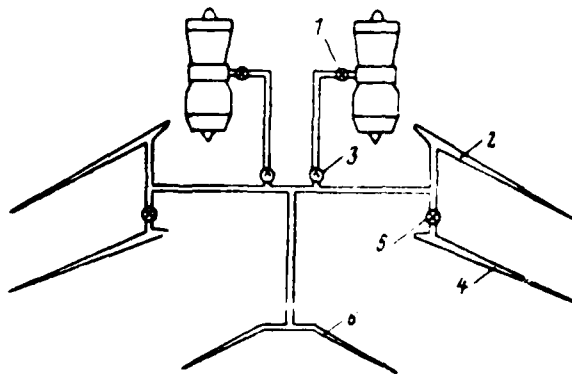


Fig. 3.36. Schematic diagram of the combined control system. 1 - locking-reduction valves, 2 - boundary layer control and warning/prevention of the icing of leading wing edge, 3 - check valves, 4 - boundary layer control in trailing wing edge, 5 - emergency fuel system valve of leading and trailing edges, 6 - boundary layer control and warning/prevention of the icing of the leading edge of stabilizer.

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The weight of installation for boundary layer control and warning/preventing the icing composes 20/o of gross weight.

Warning/prevention of icing can be also practiced during the testing of engines on the earth/ground before the takeoff.

Takeoff and landing are completed usually with the connected boundary layer control system, moreover automatically begins to work the warning system of icing.

It should be noted that during takeoff and landing with boundary layer control is utilized the maximum air pressure, selected/taken from engines, so that simultaneously there is a maximum possibility of warning/preventing the icing. The valves of the decrease of pressure work only during warning/prevention of icing. The start of this system occurs by hand in all flight conditions.

7. Thermal de-icing systems of periodic action.

The de-icing systems of periodic action according to their very operating principle are more economical from the point of view of energy input ¹.

FOOTNOTE ¹. The first Soviet thermoelectric de-icing system of periodic action, which obtained wide acceptance, was created in design bureau of A. N. Tupolev (by specialists K. Ye. Polishchuk, A. S. Payshteyn et al.). ENDFOOTNOTE.

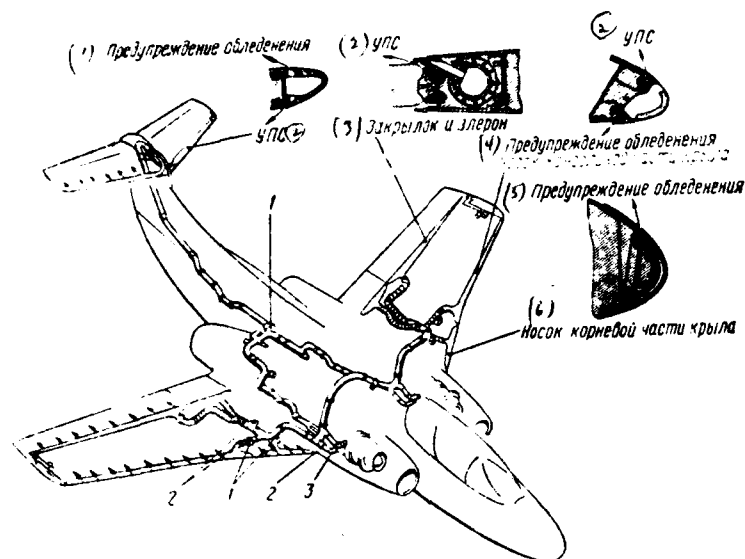


Fig. 3.37. Device/equipment of the combined boundary layer control system and warning/prevention of icing. 1 - reduction valves, 2 - check valves, 3 - air bleed from engine.

Key: (1). Warning/prevention of icing. (2). UPS. (3). Flap and aileron. (4). Warning/prevention of icing nose/leading edge of outer wing panel. (5). Warning/prevention of icing. (6). Nose/leading edge of root of wing.

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This savings is caused not only by the fact that heating its elements/cells is accomplished/realized periodically, but also fact

that for removing already formed ice is required to melt its only thin layer, directly adjacent to skin/sheathing - the disturbance/breakdown (or weakening) of the cohesion/coupling ice with surface they contribute to its dropping under the action of aerodynamic forces.

Important advantage of this type of systems is also the smaller dependence of the energy consumed by them on the conditions of icing (water content and temperature of surrounding air). If for the systems, antiicing, consumed by them a quantity of heat the greater, the greater the intensity of the increase of ice and the lower the temperature of surrounding air, then for the systems of periodic action the significant role plays only temperature, since from it directly depends during the permanent cycle of the operation of system calorific requirement for heating of the surface, covered with ice, to 0°C .

One should in this case note that this the temperature effect of surrounding air somewhat less than in the systems, antiicing, due to the heat-insulating properties of the formed layer of ice.

Since the distance of ice is accomplished/realized more easily with its larger thickness, accomplishing flight under conditions of intense icing does not present such difficulties for the systems of

periodic action as for the systems of continuous heating.

The fundamental objection, which they usually voice against the use/application of de-icing systems of periodic action, consists in the fact that in each specific case it is necessary to determine, what with the operation of system ice formation is permissible in flight. For the systems, which work with permanent cycle, setting the thickness of the permissible layer of ice, is determined under the design conditions of icing (with that accepted theoretical rate of ice build-up). For systems with a regulable cycle of work this checking it must be made with the maximum thickness of ice which allows/assumes the control.

The fundamental requirement which is presented to the de-icing system of periodic action it consists in ensuring of the complete removal of ice per cycle of the operation of system and not allowing the formation of "barrier" ice.

Let us note that the unsatisfactory results, obtained during the tests of the initial versions of cyclic thermoelectric systems, created in their in the series/row of aviation specialists negative to them relation, in spite of the positive data of the first theoretical studies (M. Traybus, F. V. Veyner, A. S. Zuyev, R. Kh. Tenishev et al.).

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Only the great experimental and test work¹, carried out both outside the boundary and on experimental designs², it showed that during the correct identification of the parameters of cyclic de-icing system it is possible to ensure its high effectiveness and efficiency/cost-effectiveness.

FOOTNOTE 1. Fundamental works in this region outside boundary were made by the English researchers of the firm Nepir (R. D. Krik, B. T. Chiverton et al.).². In majority of works indicated which were made by design bureaus of A. N. Tupolev, O. K. Antonov, S. V. Il'yushin, for author it was necessary to accept direct participation.

ENDFOOTNOTE.

Besides the savings of energy, cyclic deicer gives the possibility to warm only the small part of the surface of the leading edge of wing or tail assembly (a little more than the zone of capture/grip).

As showed experimental flights, for fulfilling of fundamental requirement indicated above the de-icing system of the periodic

action:

a) must provide high rate heating and coolings of the shielded surface;

b) have on the leading edge or wing (or tail assembly) the so-called thermal "knives" of the permanent action;

c) must provide the regulation of the cyclic recurrence of the operation of system (i.e. the time of the inclusion and disconnection) depending on the temperature of surrounding air and icing intensity.

The first two conditions are necessary for rapid or, as they say, the "shock" jettisoning of ice, also, for the exception/elimination of the runoff of water over surface for the warmed zone, since the runoff of water leads to the formation of "barrier" ice.

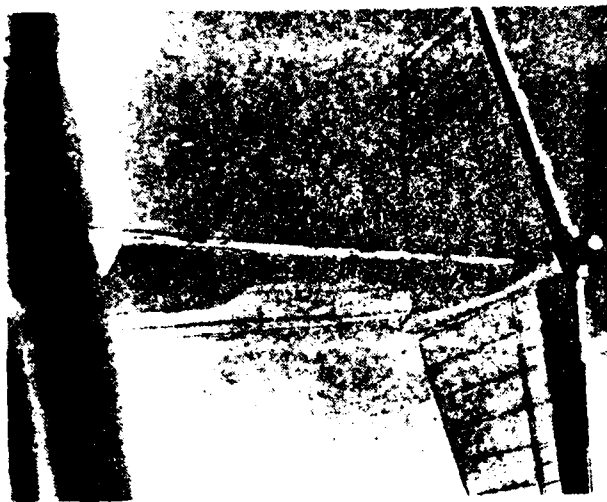


Fig. 3.38. Ice on the nose/leading edge of stabilizer.

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The third condition is necessary in order not to allow the formation/education of a layer of ice of dangerous thickness and "barrier" ice, or for guaranteeing the most rational energy consumption. Satisfaction of the third condition can be achieved/reached by the use/application of certain permanent "compromise" short cycle of the operation of system.

If in system is not fulfilled any of the enumerated conditions, then appears icing (Fig. 3.38, 3.39 and 3.40). All photographs are obtained in the connected de-icing system.

Three necessary conditions are more simple to carry out in thermoelectric ones, than in the air-heat systems. A shortcoming in the air-heat deicer is its inertness - slow heating upon start and slow cooling after disconnection (Fig. 3.41 and 3.42). As can be seen from the graph Fig. 3.42 even at the identical specific power of heating ($W_{yd} \approx 1 \text{ W/cm}^2$) the intensity of heating in the air-heat de-icing system considerably less than in thermoelectric. Fig. 3.43 gives the rates of heating skin of the nose/leading edge of stabilizer under identical flight conditions (in "dry" air) for the thermoelectric de-icing system, established/installed on three aircraft types (Tu-114, Il-18 and An-10).

The typical graph of a change in the temperature drop in time with the operation of cyclic system is given in Fig. 3.44 for the aircraft of An-10 whose cyclic recurrence composes 40:120 (40 s it is connected, 120 s it is switched off), and for the aircraft of Tu-114 with cyclic recurrence 20:220.



Fig. 3.39. Barrier ice on stabilizer.

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Fig. 3.40. Barrier ice on blades of propeller and its cook.

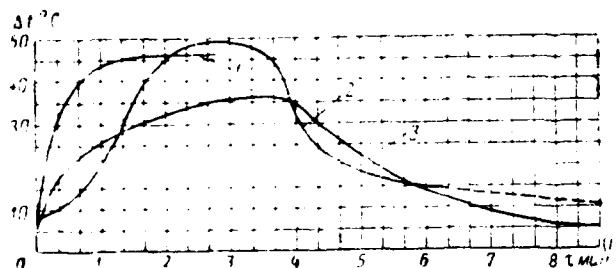


Fig. 3.41. Rate of heating and cooling in "dry" air of skin/sheathing of wing leading edge in air-heat de-icing system. 1 - An-10 ($H=1700$ m, $V_{\text{кр}}=200$ km/h), 2 - Tu-104 ($H=5000$ m, $V_{\text{кр}}=200$ km/h), 3 - Il-14 ($H=1500$ m, $V_{\text{кр}}=200$ km/h).

Key: (1). min.

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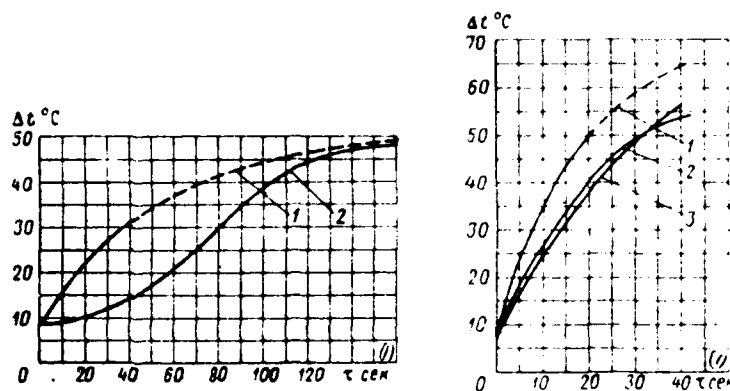


Fig. 3.42. Rate of heating skin of wing leading edge in different de-icing systems ($H=5000$ m, $V_{up}=400$ km/h, $W_{V1} \approx 1$ W/cm²). 1 - thermoelectric system of the wing of the aircraft of Tu-114, 2 - air-heat system of the wing of the aircraft of Tu-104.

Key: (1). s.

Fig. 3.43. Rate of heating skins of nose/leading edge of stabilizer in thermoelectric de-icing system ($H=5000$ m, $V_{up}=400$ km/h, thermal "knives" are switched off). 1 - Tu-114 ($W_{V1}=2.3$ W/cm²), 2 - Il-18 ($W_{V1}=1.2-1.15$ W/cm²), 3 - An-10 ($W_{V1}=1.5$ W/cm²).

Key: (1). s.

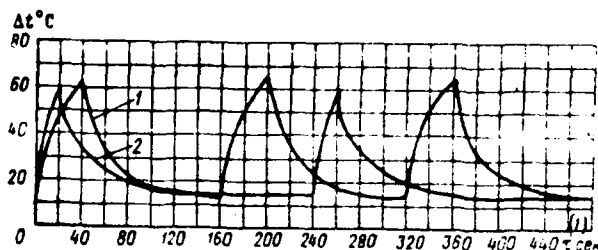


Fig. 3.44. Rate of heating and cooling in "dry" air of skin/sheathing of the nose/leading edge of stabilizer in thermoelectric de-icing system ($H=5000$ m, $V_{\text{app}}=400$ km/h). 1 - An-10, cyclic recurrence 40:120, 2 - Tu-114, cyclic recurrence 20:220.

Key: (1). s.

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Let us examine, what are required temperature drops in "dry" air for cyclic deicers, in order to ensure their effective work under conditions of icing.

Fig. 3.45 gives temperature drops on the nose/leading edge of the stabilizer of the aircraft of Tu-114, Il-18 and An-10 for two versions of prototype systems - heating of cyclic element/cell 0.5-0.8 W/cm² initial with the specific power and new with the increased specific power (to 2.3 W/cm² for Tu-114 and to 1.2-1.5 W/cm² for Il-18 and An-10). As we see, temperature drop sharply increased, approximately, to 60°C.

Fig. 3.46 gives a change in the derivative of temperature drops in time, which characterizes by those of heating the noses/leading edges of the stabilizer of the aircraft indicated upon the start of de-icing system. From graph it is evident that the highest rate of heating by 1-3°C per second has a deicer of the aircraft of Tu-114.

The tests of de-icing systems with the increased power of heating on all three aircraft types indicated showed that the distance of ice per cycle of work was provided under conditions of icing to the temperatures of surrounding air on the order of -20°C . In this case on the aircraft of An-10 and Il-18 was noted the appearance on the unheated part of the stabilizer under some conditions for barrier ice flows. But the aircraft Tu-114 in connection with the higher rate of heating and the short period of the start (20 s) of this phenomenon discovered did not have.

On the basis of the analysis of the measured temperature drops and data from the work of cyclic deicers under conditions of natural icing it is possible to consider that the value of the required temperature drop, attained for the heating time, must in "dry" air comprise not less than 60°C at the rate of heating by $2-3^{\circ}\text{C}$ per second, in order to ensure jettisoning ice in cycle at temperatures of surrounding air on the order of -20°C . Under the more severe conditions of icing, obviously, will be required large temperature drops.

For that used in the series/row of the aircraft of the so-called "sandwich" construction of thermoelectric deicers it is of interest setting the connection/communication of temperature drops with the required specific power of the heating of cyclic heating element

(Fig. 3.47).

FOOTNOTE 1. See below the description of thermoelectric de-icing system. ENDFOOTNOTE.

From graph it follows that an increase in the effectiveness of system (increase in the temperature drop with shortening of the heating time) is connected with the very large specific powers of heating element. This is a shortcoming in the system of the datum of construction/design and testifies about its considerable thermal inertness and large heat losses in it.

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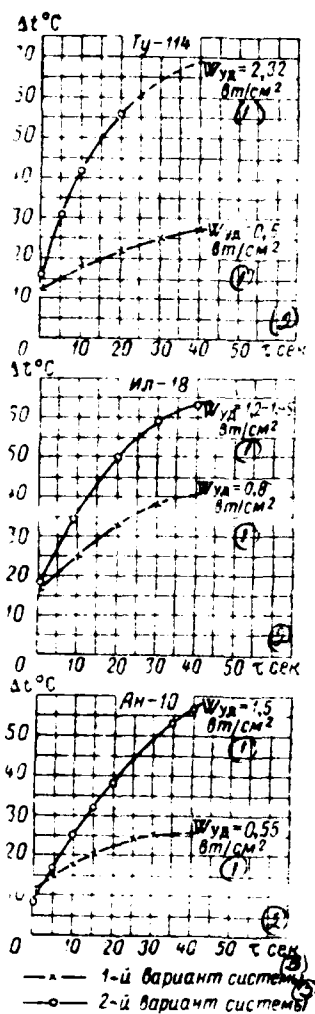


Fig. 3.45.

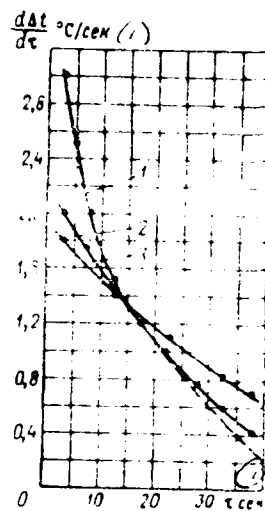


Fig. 3.46

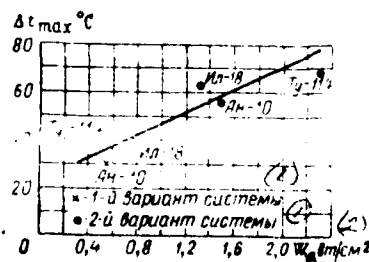


Fig. 3.47

Fig. 3.45. Temperature drops on lateral surface of noses/leading edges of stabilizer of aircraft Tu-114, Il-18 and An-10 ($H=5000 \text{ м}$,

$V_{\text{кр}} = 400 \text{ км/ч}$).

Key: (1). W/cm^2 . (2). s. (3). version of system.

Fig. 3.46. Derivative $\Delta t/dt$ of temperature drops on lateral surface of noses/leading edges of stabilizer with thermoelectric de-icing system ($H=5000$ m, $V_{max}=400$ km/h). 1 - aircraft of Tu-114, 2 - aircraft of Il-18, 3 - aircraft of An-10.

Key: (1). s.

Fig. 3.47. Maximum temperature drops Δt_{max} on lateral surface of nose/leading edge of stabilizer depending on specific power of cyclic heating element W_{cyc} ($H=5000$ m, $V=400$ km/h).

Key: (1). version of system. (2). W/cm^2 .

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The second important factor of an increase in the effectiveness of cyclic deicer, as already mentioned, is the use/application of the thermal "knives", which are the narrow continuously warmed zones, situated along leading edge and on the joints of heating elements. Such "knives" - divide into parts the ice build-up forming on leading edge and thereby they facilitate its dropping under the effect of air flow (Fig. 3.48).

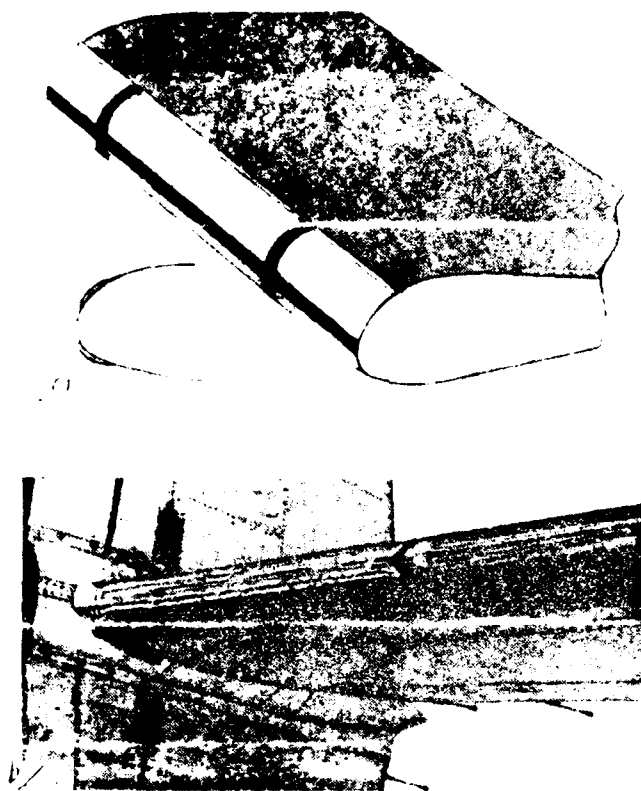
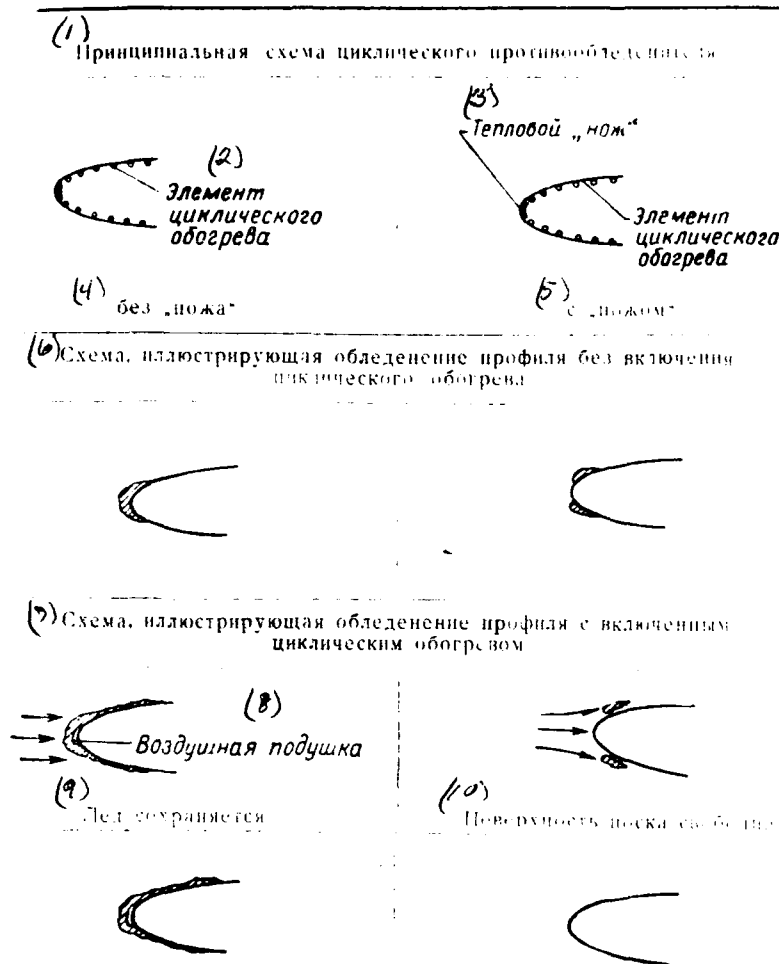


Fig. 3.48. The standard diagram of cyclic heater with thermal "knives" (a) and the photograph (b), which illustrates the action of longitudinal thermal "knife" in flight under conditions of the heater (cyclic heating is switched off).

Table 12 gives the outlines, which illustrate the effectiveness of cyclic deicer with "knives", also, without it.

De-icing system with "knives" in Soviet aircraft construction was for the first time proposed and investigated by R. Kh. Tenishev and author of this book on one of experimental designs, developed by the collective of design bureau of O. K. Antonov.

Table 12.



Key: (1). Schematic diagram of cyclic deicing. (2). Element/cell of cyclic heating. (3). Thermal "knife". (4). without "knife". (5). with "knife". (6). Diagram, which illustrates icing of profile/airfoil without start of cyclic heating. (7). Diagram, which illustrates

icing of profile/airfoil with connected cyclic heating. (8). Air cushion. (9). Ice is retained. (10). Surface of nose/leading edge is free.

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During the development of cyclic de-icing systems for the sweptback wings (tail assemblies) was voiced the opinion that in this case the installation of the thermal "knives" of permanent action is not necessary, since jettisoning ice will be facilitated by the presence of the component of air flow, directed along the span of wing (tail assembly). Actually/really, observations of the trajectories of those jettisoned from the leading edge of the sweptback wing of the pieces of ice attest to the fact that the component indicated contributes to the distance of ice in direction on the wingspan. However, as showed special experiments on the stabilizer of the aircraft of Tu-114, thermal "knife" at the sweep angle of wing of 40° it proved to be necessary for the effective work of cyclic deicer. In spite of the large specific powers of heating (2.8 W/cm^2) at temperature of surrounding air is lower than -15°C deicer of right half the stabilizer (where the thermal "knife" was absent) it did not provide the distance of ice, while the deicer of the left half stabilizer (with thermal "knife") effectively dumped ice within the time, which did not exceed 20 s.

The important special feature/peculiarity of the operation of cyclic de-icing systems is the need for their timely start. Upon overdue start the effectiveness of the action of systems sharply descends, and the distance of ice can engage not 20-40 s, as usual, but several minutes. This it requires on the one hand of installation on the aircraft of highly sensitive reliable ice-indicating equipment. On the other hand, in recommendation for a pilot must be introduced the indication about the start of cyclic de-icing systems either prior to the entry of aircraft into cloudiness when the minus temperatures of surrounding air are present, or at the very beginning of icing.

One of important promising questions is the development of a signal indicator-automatic machine, which ensures the automatically timely start of de-icing system and control its work in dependence on the icing intensity and temperature of surrounding air. It was until recently for designers yet impossible to successfully solve this question mainly due to the absence of reliable ice-indicating equipment.

Another problem is the development of this cyclic air-heat de-icing system which would make it possible to considerably reduce

the required quantity of hot air, selected/taken from engines. Fig. 3.49 gives one of the possible schematics of the air-heat de-icing system of cyclic action with longitudinal thermal "knife".

As examples let us examine several typical thermoelectric de-icing systems, used on contemporary aircraft.

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The thermoelectric de-icing system of the tail assembly of the aircraft of An-10 consists of the heating elements of cyclic and permanent heating. "thermal knives" are arranged/located along the leading edges of stabilizer and fin, and also on the joints of the sections, warmed cyclically. The diagram of the layout of heating elements is given in Fig. 3.50.

The cyclic electrical heating elements/cells of stabilizer and fin are developed in 3 sections, included consecutively/serially: first the end sections of stabilizer and the root section of fin, then - middle sections, further - the root sections of stabilizer and the middle section of fin and finally the end section of fin and washer.

The complete cycle of the work of deicer occurs thus for 4

impulses/momenta/pulses. Feed/supply of de-icing system is accomplished/realized from mains of direct current by a voltage 27 V. The cyclic inclusion of sections is provided by the programmer, which assigns cyclic recurrence 40:120 (each section 40 s is found under voltage and 120 s - in the de-energized position).

The electrical circuit diagrams of cyclic heating elements and tapes of permanent heating - thermal "knives" are represented in Fig. 3.51 and 3.52.

the deicers of the noses/leading edges of tail assembly are the multilayer construction/design, formed by two metal coverings (with an external thickness of 0.8 mm and with an internal thickness of 0.3 mm), between which is located: an electrical insulating layer (two layers of glass cloth with a thickness of 0.3 mm), "knife" heating element, second electrical insulating layer (two layers of glass cloth with a thickness of 0.3 mm), cyclic heating element and thermal insulation layer (4 layers of glass cloth with a thickness of 0.3 mm).

Cyclic element/cell is the wire heater, which is of two brass bushbars/tires with the grid soldered to them from the constantan wire with a diameter of 0.15 mm. In the locations of "knives" wire element/cell is not distant, i.e., is provided the intensive heating

of leading edges during the work of cyclic sections.

The specific power of cyclic heating elements is permanent all over heating surface and is 1.5 W/cm² on stabilizer 1 W/cm² on fuller's earth.

The longitudinal thermal "knives", arranged/located along span of horizontal stabilizer and fin, are made from by the stainless steel thickness of 0.2 mm and with a width of 13 mm. Specific electrical power of their heating - 1.2 W/cm².

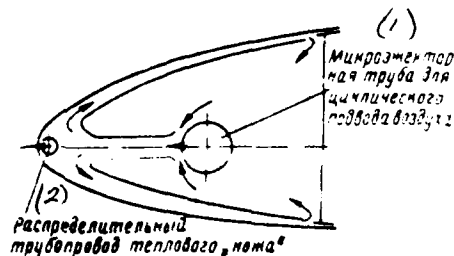


Fig. 3.49. Schematic of the air-heat de-icing system of cyclic action.

Key: (1). Micro-ejector tube for the cyclic supply of air. (2). Distributing pipe of thermal "knife".

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The transverse thermal "knives" are also made from by the stainless steel thickness of 0.3 mm and with a width of 35 mm. The specific power of the heating of their - 1.23 W/cm².

The warmed zone occupies 7-100/o of stabilizer chord and fin.

The thermoelectric de-icing system of the stabilizer of the aircraft of Tu-114 also consists of the cyclically warmed elements/cells and the thermal "knives" of permanent heating which are arranged/located along span of horizontal stabilizer. In contrast

to the system examined above on the aircraft An-10 this de-icing system does not have transverse thermal "knives".

The elements/cells of the cyclic heating of stabilizer are broken in 8 sections, included consecutively/serially. Cyclic feed/supply is provided by the special program unit, which includes the heating of each section on 20 s. During subsequent 220 s the section is cooled.

The deicers of noses/leading edges are the multilayer construction/design, pressed during heating in vacuum, analogous to the deicers, established/installed on the aircraft of An-10 (Fig. 3.53). Cyclic electrical heating elements/cells are made from the constantan wire with a diameter of 0.15 mm, soldered to brass power buses. In the center section of the elements/cells under "knife" the wire is distant.

The space of the coil/winding of wire - variable/alternating provides the distribution of specific electrical powers of heating element in limits from 2.9 W/cm² (it is direct in leading edge) to 1.7 W/cm² (at the end of the warmed zone).

The thermal "knife" of permanent action, established/installed along span of horizontal stabilizer, is made from the brass foil with

a width of 20 mm. Specific electrical power of the heating of "knife"
- 1.8 W/cm². Feed/supply or cyclic heating elements and "knife" is
accomplished/realized from mains or direct current by a voltage 27 V.

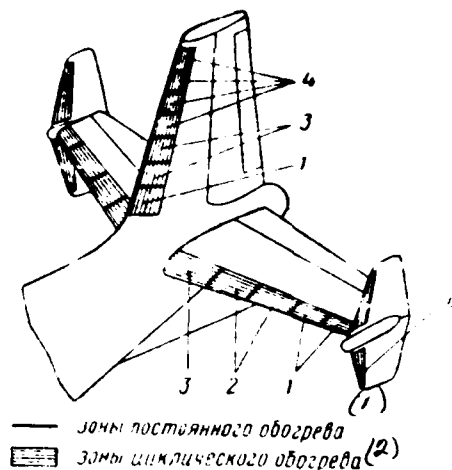


Fig. 3.50. Diagram of the layout of heating elements, which are located on the tail assembly of the aircraft of An-10. 1 - end sections of stabilizer and root section of fin, 2 - middle sections of stabilizer, 3 - middle section of fin and root sections of stabilizer, 4 - end section of fin and washer.

Key: (1). the zone of permanent heating. (2). zone of cyclic heating.

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The power, consumed by thermal "knife", composes 5.92 kW, cyclic heating elements -6.6-8.9 kW.

Fig. 3.54 gives the graph, which shows distribution the temperature drops according to carrying of stabilizer upon the start

of cyclic and permanent heating.

For protection from the icing of the tail assembly of aircraft "Britain", "Vanguard", "Argosy" and series/row of other foreign aircraft are applied electrical heating coatings of the type "Spraymat", made by the English firm Nepir [a guess] [51], [37].

Coatings Spraymat will be deposited directly to skin/sheathing of the aircraft components, shielded from icing, and are connected the constantly warmed zones and the zones of cyclic heating.

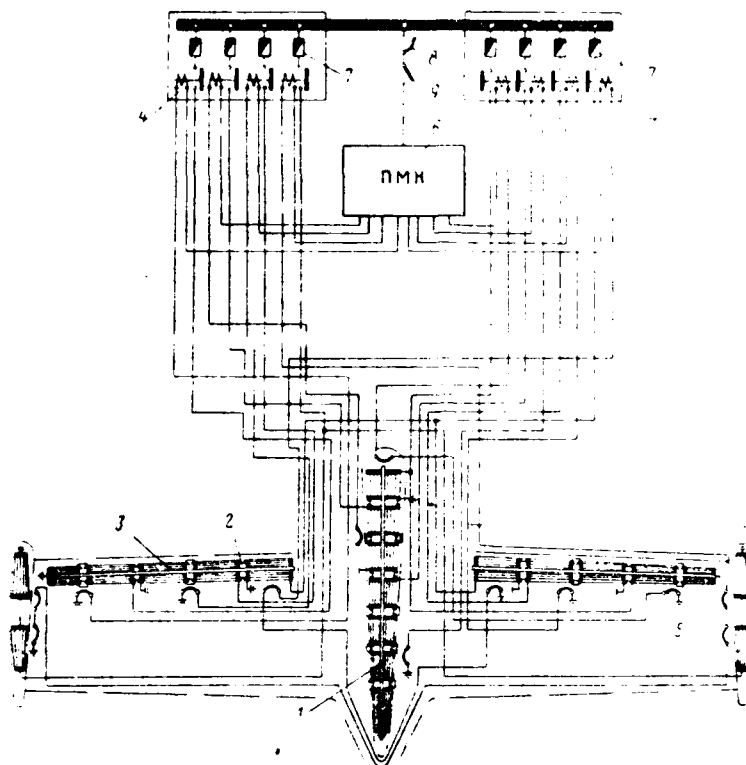


Fig. 3.51. Electrical circuit diagram of the cyclic heating of the tail assembly of the aircraft of An-10. 1 - longitudinal members of permanent heating, 2 - cross members of permanent heating, 3 - elements/cells of cyclic heating, 4 - contactors, 5 - thermoswitches, 6 - programmer, 7 - safety fuses, 8 - automatic machine of protection, 9 - switch.

Technology of the manufacture of coatings following. Is first cleaned the surface of nose/leading edge by the method, analogous to the method of working/treatment by sand blasting, will be deposited a layer of cement, also, to it a layer of electro-insulation (glass cloth, saturated with liquid plastic). Before the patch of glass cloth under it at several points, usually under thermal "knives", are embedded the thermistors for the protection of the warmed aircraft components of superheating upon start on the earth/ground.

The gluing of fiber glass fabric is accomplished/realized under pressure with the aid of the special elastic tanks/balloons, inflated by air, at temperature on the order of 150°C. After drying of surface it is ground.

Further is produced the marking of surface for arrangement/position on the nose of electrical heating elements/cells in accordance with the sizes/dimensions, indicated on drawing. To a layer of insulation/isolation will be deposited separational stripes (with a width of 2-3 mm) from the adhesive, durable paper or from plastic with purpose of ensuring in production electro-insulation between separate heating elements. Then by the method of pulverization will be deposited that conducting current it is accomplished/realized with the aid of the special pistol to which are fed/conducted the wire with a diameter of 2 mm from the alloy indicated, and also three noses for supplying gaseous products of atomization.

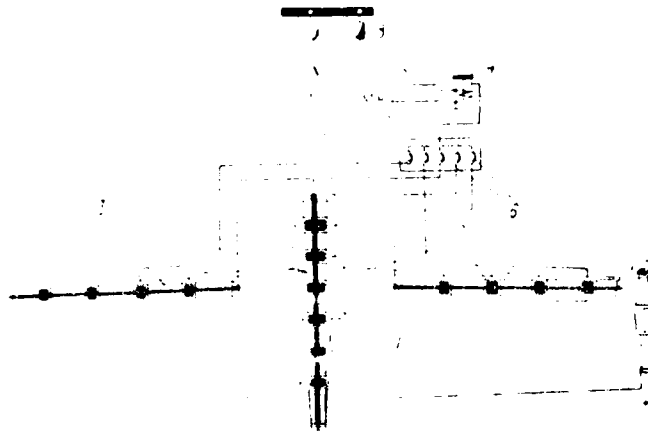


Fig. 3.52. Electrical circuit diagram of the longitudinal and transverse heating elements of permanent heating (thermal "knives") on the tail assembly of the aircraft of An-10. 1 - longitudinal members of permanent heating, 2 - cross members of permanent heating, 3 - elements/cells of cyclic heating, 4 - contactor, 5 - program mechanism, 6 - automatic machine or protection, 7 - switch, 8 - safety fuse.

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In coating by special probes is measured the resistance of each section of coating. Pulverization/atomization continues until resistance on achieves the assigned magnitude.

Heating elements in the form of the bands with a width of 25 mm are connected between themselves by the copper busbars/tires with a width of 8 mm whose designation/purpose to remove the nonuniformity of heating in points of connections.

After application of the current-conducting layer are removed boundary strips and will be deposited on top an electrical insulating layer similar to the first layer of insulation/isolation. Then will be deposited abrasion-resistant coating (powder of the stainless steel in mixture with synthetic resin) and is produced drying and coloration. The overall thickness of coating is ~1.5 mm. The applied protective coatings are sufficiently solid, but they are brittle, and therefore they can be damaged from the impacts/shocks of the solid particles, which fly at a high speed. This is an essential shortcoming in the coating.

The specific powers of the heating of the deicers of firm "Nepir" comprise, as a rule, 1.5-1.8 W/cm² for constantly warmed zones ("knives") and 1.7-2.5 W/cm² - for the cyclically warmed zones. The size of the warmed zone is usually within the limits by 12-15% of chord. Firm selected the cyclic recurrence of work of deicers 1:10; 1:15 with the time of heating 15-20 s.

Feed/supply of deicers is accomplished/realized by a three-phase

alternating current of voltage 200 V (400 Hz). This substantially decreases the weight of electric wires and in combination with the use of a system of cyclic action gives the large savings of electric power.

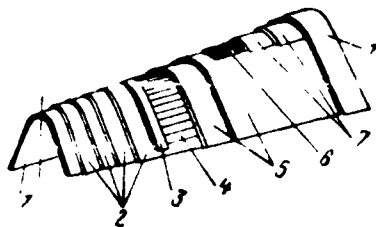


Fig. 3.53

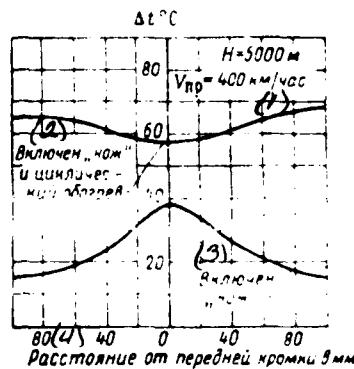


Fig. 3.54.

Fig. 3.53. Construction/design of the deicer of the nose/leading edge of the stabilizer of the aircraft of Tu-114. 1 - skin/sheathing; by $\delta=0.5$ mm, 2 - glass cloth $\delta=0.3$ mm, 3 - busbar/tire, 4 - cyclic heating element, 5 - glass cloth $\delta=0.3$ mm, 6 - thermal "knife", 7 - glass cloth $\delta=0.1$ mm.

Fig. 3.54. Distribution of maximum temperature drops according to carrying of stabilizer of aircraft of Tu-114 in flight in "dry" air.

Key: (1). km/h. (2). Is connected "knife" and cyclic heating. (3). Is connected "knife". (4). Distance from leading edge 8 mm.

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Coatings "Spraymat" are characterized by the high effectiveness of action with the insignificant thermal inertness of deicer.

However, on reliability and mechanical strength they are inferior to the multilayer constructions/designs of the deicers, used in the series/row of Soviet aircraft.

Let us pause in greater detail at the construction/design and the parameters of the deicers on the tail assembly of aircraft "Britannia", "Vanguard" and "Argosy".

Into the aircraft "Britannia" the shielded surface of the tail assembly is divided into three zones: the first zone - the continuously warmed sections (thermal "knives"); the second zone - sections, warmed periodically with the relationship/ratio of the time of heating and time of cooling 1:15; the third zone - also periodically warmed sections, included only under the severe conditions of icing (Fig. 3.55).

The first zone is the continuously warmed bands with a width of 25-35 mm, which pass along the leading edge of stabilizer and fin and along chord in the sites of the joints of electrical heating elements/cells. The specific power of the heating of bands 1.55-1.80 W/cm².

The second zone encompasses 70% of airfoil chord at the specific power of heating 1.7-2 W/cm². The third zone occupies

following 70/o of chord and is warmed only in the case of the formation of barrier ice (as a result of the runoff of moisture from the surface of the second zone).

Important fact is the fact that the time of heating the second zone can be changed in dependence on the temperature of surrounding air. At temperature of surrounding air of higher than -10°C time of the start of the heating of each section is 15 s, at temperature from -10 to -20°C - 22.5 s and at temperature of surrounding air from -20° to -30°C - 30 s. In this case the cyclic recurrence is retained the constant/invariable by 1:15.

The required electrical power in impulse/momentum/pulse 18.92 kW, current strength in impulse/momentum/pulse 90.8 a (58.2 a consume "knives" and 32.6a - elements/cells of cyclic heating).

On aircraft "Vanguard" the specific power of the heating of cyclic elements/cells is higher than on aircraft "Britain", and it is 2.35-2.5 W/cm². The zones of continuous heating (thermal "knives") have the variable/alternating specific power on span, which comprises for a fin 1.45 W/cm² in root and 1.8 W/cm² in end/lead and for a stabilizer 1.55 W/cm² in root and 2 W/cm² in end/lead.

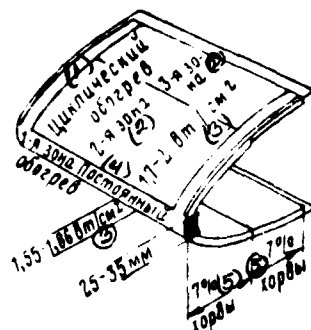


Fig. 3.55. Schematic of the heating of leading edges of the tail assembly of aircraft "Britannia".

Key: (1). Cyclic heating. (2). zone. (3). W/cm². (4). 1st zone permanent heating. (5). chords.

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This distribution of the specific powers according to span is dictated by the necessity of the more intense protection of the end sections of tail assembly.

The diagram of the layout of heating elements on the tail assembly of aircraft "Vanguard" is given in Fig. 3.56. The de-icing system consists of ten separate sections - four on fuselage's earth and six on stabilizer.

The bands of continuous heating are arranged/located along the leading edge of stabilizer and fin and along chord in the sites of the joints of the sections or cyclic heating.

Cyclic recurrence or work of heater 1:12. Depending on the conditions of icing can be selected one of the two possible versions of cyclic recurrence 10:120 (10 s heating, 120 s cooling) or 20:240 (20 s heating and 240 s cooling). The modes/conditions of cyclic recurrence change by hand with the aid of switch, which is located in cockpit. Thus, one complete cycle occurs each 130 or 260 s. Heating elements on fuller's earth are arranged/located symmetrically relative to the leading edge; on stabilizer due to the presence of the negative angle of stabilizer setting the warmed zone to upper surface is more than on lower.

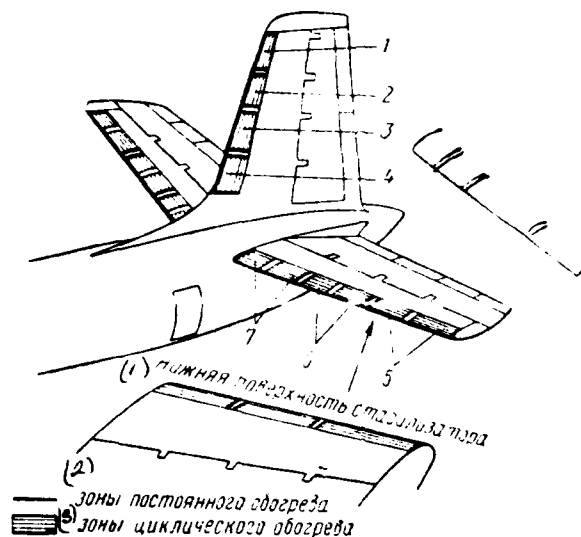


Fig. 3.56. Diagram of the layout of heating elements on the tail assembly of aircraft "Vanguard". 1 - upper section of fin, 2 - middle upper section of fin, 3 - middle lower section of fin, 4 - root section of fin, 5 - end section of stabilizer, 6 - middle section of stabilizer, 7 - internal section of stabilizer.

Key: (1). Lower surface of stabilizer. (2). zone of permanent heating. (3). zone of cyclic heating.

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For the protection of noses/leading edges the tail assemblies from the possible damage by hail or solid particles, available on

VPP, in the zone with a width of 165 mm sverxu and from below from leading edge will be used the special protective coating Standquard of the firm of Nepir.

The power, consumed by deicer, does not exceed 34.2 kW of them of 18.5 kW it consumes cyclic system and 15.7 kW - thermal "knives". If heating entire deicer was produced continuously, then it would be required by 218 kW of electric power.

The twin-finned tail of aircraft "Argosy" also has the de-icing system of the firm Nepir - coating Spraymat.

The deicer of tail assembly consists of two independently working systems: the first system encompasses the nose/leading edge of stabilizer on spread/scope with a length of 7.14 m, the second - noses/leading edges of both fins, horn elevator balances and remaining sections of the leading edges of stabilizer, which adjoin the fin from internal and face. The total shielded area is 8.15 m² and is divided almost equally between two systems (3.95 m² - system No. 1 and 4.19 m² - system No. 2).

Each system consists of ten cyclically warmed zones with the bands of continuous heating to leading edge, also, along chord of the sites of the joints of heating elements.

The laying out of the shielded surface of tail assembly to zones and the sequence of their starts are given in Fig. 3.57. As can be seen from figure, the start of the heating of zones and, consequently, also jettisoning ice in these zones occurs asymmetrically relative to longitudinal axis of aircraft and also relative to the leading edges of stabilizer and fin.

In de-icing system there are two cyclic switches to 10 positions - on one to each system.

Electric power is developed by four a-c generators, established/installed one on each power plant.

Table 13 gives the required powers for de-icing systems.

The specific power of the heating of all cyclic zones is 2.75 W/cm², the bands of permanent heating - 1.24 W/cm² for stabilizer and 1.45 W/cm² for a fin (1 W/cm² in root and 1.45 W/cm² in the end/leaf of the fin).

The sections of the deicer of the tail assembly of aircraft "Argosy", the same as of aircraft "Vanguard", are made directly with

the construction of aircraft.

The construction/design of the deicer of nose/leading edge is represented in Fig. 3.58.

The de-icing system of the wing of aircraft C-133A "Cargomaster" with four turboprop engines - is air-heat of cyclic action.

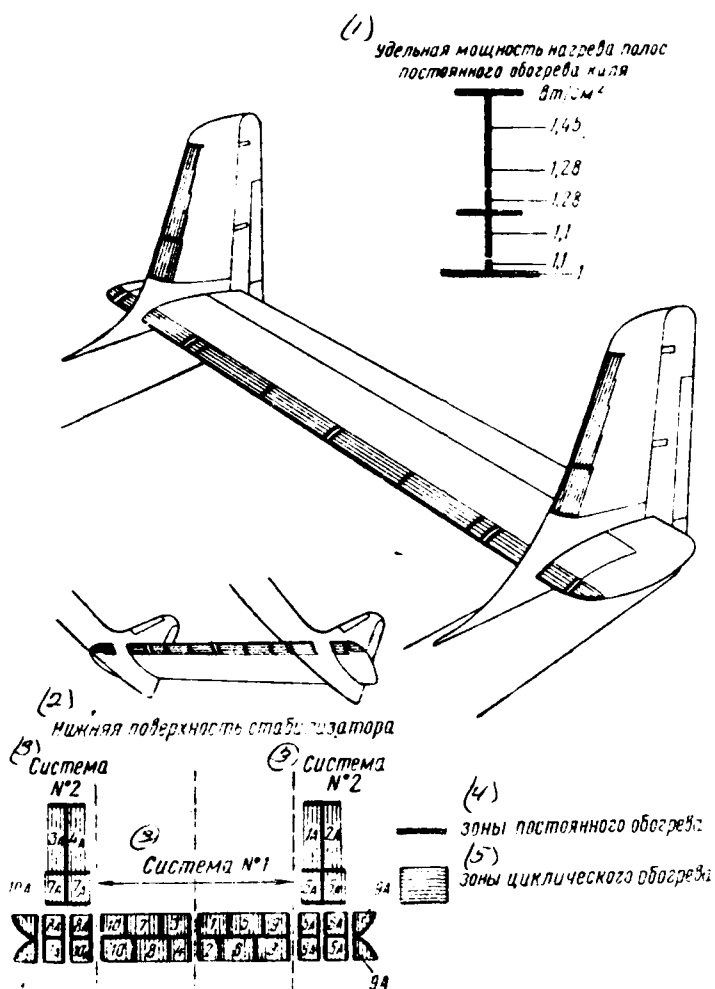


Fig. 3.57. Diagram of the layout of heating elements on the tail assembly of aircraft "Argosy".

Key: (1). The specific power of heating the bands of the permanent heating of fin W/cm². (2). Lower surface of stabilizer. (3). System.

(4). zone of permanent heating. (5). zone of cyclic heating.

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For protection from icing is utilized the hot air, selected/taken from the compressors of engines. The de-icing system of the combined action, it provides the continuous heating of leading edge and cyclic - lateral surface of the wing leading edges.

The schematic diagram of de-icing system is given in Fig. 3.10.

The air, selected/taken from engines, through reverse/inverse and locking 3, 3 valves enters distributing pipe, from which then air falls into the wing leading edges.

To leading wing edge the air enters through eight pneumatic valves 5 and 7, controlled by solenoids. In the system of the continuous heating of leading wing edge are thermostats, which close the valves of air supply at temperature of surrounding air at higher than -4°C .

The signaling of the open position of valves is accomplished/realized with the aid of the special indicators, arranged/located on the control panel of the de-icing system of wing

and tail assembly on the instrument panel of flight engineer (on one to each half wing).

The cyclically warmed zone of the wing leading edge is divided in 12 sections (on 6 to one half wing) by length, approximately/exemplarily, by 3.7 m. Air is supplied on 12 conduits/manifolds through pneumatic valves 4 and 6, the controlled timers which alternately supplies feed/supply to each valve. Timer connected with the temperature-sensing device, mounted in right landing-gear fairing, and actuates the valves of cyclic de-icing system in the determined order and on the specific time, which depends on the temperature of surrounding air. The cycle of opening begins with the outer valve of right half wing and concludes with the valve of left half wing near the fuselage. Timer always begins the cycle of valve opening in this sequence, if the preceding/previous cycle was completed to the disconnection of system.

Table 13.

(1) Противообледенительная система	(2) Затрачиваемая мощность в зоне	
	(3) постоянного обогрева	(4) обогреваемой циклически
№ 1	(5) 4,8 кВт (от генератора № 4, нормально и № 1 в аварийном случае)	(6) От 9,9 до 10,1 кВт (от генератора № 1, нормально и № 4 в аварийном случае)
№ 2	(5) 7,1 кВт (от генератора № 2, нормально и № 3 в аварийном случае)	(6) От 9,1 до 10,4 кВт (от генератора № 1, нормально и № 2 в аварийном случае)

Key: (1). De-icing system. (2). Spent power in zone. (3). permanent heating. (4). warmed cyclically. (5). 4.8 kW (from generator No. 4, normally and No. 1 in emergency case). (6). From 9.9 to 10.1 kW (from generator No. 1 it is normal and No. 4 in emergency case).

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Thus, jettisoning from wing occurs unsymmetrically relative to the longitudinal axis of aircraft.

If necessary for continuous operation of deicer or malfunction of timer is provided for the emergency system, hand-operated, with the aid of which simultaneously, are opened all valves and are closed the valves of air supply to the leading edge of the wing leading edge. In this case necessary visually to follow the wing and to turn

off/disconnect heating, as soon as ice it will be distant.

System is shielded from superheating by the thermostats, arranged/located on the lower side of the lower covering in the middle of each section. During heating of the sensor of thermostat to temperature of 60°C switches, been connected in series with valves, are broken and they close the latter/last not later than within three seconds.

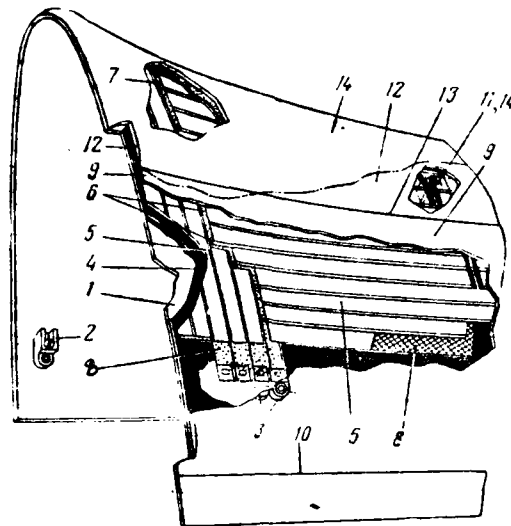


Fig. 3.58. Construction/design of the deicer of the nose/leading edge of aircraft "Argosy". 1 - section of nose/leading edge, 2, 3 - terminal boards, 4 - internal insulating layer, (2 layers of the glass cloth, saturated with plastic), 5 - current-conducting elements/cells from the alloy, sprayed on the actions of flame, 6, 7, 8 - copper busbars/tires, applied by pulverization/atomization under the action of flame above the current-conducting layer, 9 - external insulating layer (1 layer of the glass cloth, saturated with plastic), 10 - boundary of insulating layer, 11 - terminal of the grounding of protective coating (Stanguard), 12 - protective coating (Stanguard), which consists of the powder of the stainless steel, connected with synthetic resin, 13 - boundary of protective coating

(Stanguard), 14 - paint and varnish coat.

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In the valves of air supply in wing panel are limit switches, file closers circuit to two indicators of the normal operation of valves "left half wing" and "right half wing". Indicators give readings depending on the position of valves "opened" or "closed" during entire time of its work.

The operation of valves can be checked on the earth/ground or in flight with the aid of the switches of checking the valves of leading edge and cyclic wing panels (momentary contact switch).

8. Some comparative data along the air-heat and thermoelectric de-icing systems.

The setting up of de-icing system unavoidably causes a deterioration in flight-technical and operational data of aircraft as a result of the decrease of thrust or power (if the energy source for a system is airplane engine), increase in the consumption of fuel, gain in weight and complication of construction/design.

A deterioration in these data will be different depending on the type of de-icing system and specific characteristics of aircraft and it can be brought to the minimum during correct design.

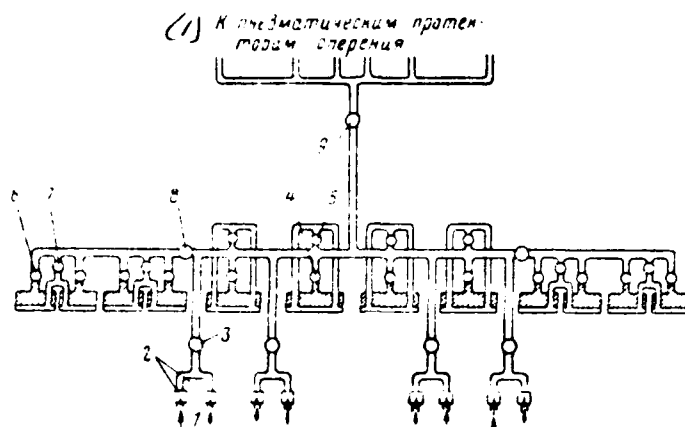


Fig. 3.59. Schematic diagram of the de-icing system of the wing of aircraft "Cargomaster". 1 - air bleed from engines to the heating of wing, 2 - check valves, 3 - check valves in the system of air bleed, of engine, 4 - locking-reduction valves of center section, 5 - locking-reduction valves of the leading edge of center section, 6 - locking-reduction valves of outer wing panel, 7 - locking-reduction valves of the leading edge of outer wing panel, 8 - locking-reduction valves of outer wing panel, 9 - locking-reduction valve of tail assembly.

Key: (1). To pneumatic protectors of tail assembly.

There are three fundamental methods of the selection of energy

from turbojet engine for the de-icing system:

- 1) the use of mechanical energy from the shaft of compressor and its transformation into the electrical;
- 2) the use of the heated air from the compressor of the engine;
- 3) use of thermal energy of exhaust gases.

The first method requires the setting up of sufficiently powerful/thick generators, especially if it is possible to shield from icing large surfaces (wing, tail assembly).

Simple calculation shows that for a thermoelectric continuous system would be required the too powerful/thick electric power sources, setting up which it is difficult to carry out on contemporary aircraft. Therefore all at present thermoelectric de-icing systems of wing and tail assembly used are systems of cyclic action.

Is most simple the second method, since it does not require any supplementary settings up - the air, selected/taken from compressor and which has temperature of 150-200°C, directly is utilized in de-icing system.

Using the third method the exhaust gases are abstracted/removed from jet nozzle. In this case, since the temperature of gases is too high, then they must be mixed with the specific quantity of cold air. Due to possible corrosion of conduits/manifolds and construction of the aircraft this method did not receive wide acceptance. Another way of using heat energy of exhaust gases - use/application of heat-exchanger, placed on the exhaust of the engine, in which is heated the air, which comes from velocity head. The de-icing system of this diagram is realized, for example, on aircraft "Vanguard" and "Argosy".

Let us pause in somewhat more detail at comparative data of two types of de-icing systems, which obtained widest acceptance on contemporary aircraft - continuous air-heat and thermoelectric (cyclic).

Effectiveness of the action of de-icing systems.

During comparison let us proceed from the fact that each system must ensure protection from icing under the calculated conditions accepted.

The advantage of thermoelectric de-icing system consists in the fact that available electric power virtually does not depend on engine power rating, height/altitude, flight speed, temperature of surrounding air. For the air-heat system with air bleed from the compressor of turbojet engine the available heat almost is proportional to atmospheric density and directly it depends on engine revolutions.

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Thermoelectric de-icing system possesses the higher heat availability factor (especially the system of the type "Spraymat" whose heating elements are arranged directly on the shielded surface and which has low heat losses).

Requirements for energy.

For the thermoelectric cyclic system there is required several times less energy than for the air-heat continuous system.

The smallest requirement for heat for the air-heat system is reached in the case of the complete evaporation of the drops of water over the area of their settling. however, it is very difficult to provide heating sufficient for evaporating the drops with warm air of

the low sections of surface. One should in this case consider that on the one hand for strength reasons for constructions/designs of the aluminum alloys the temperature of the air, which enters the system, must not exceed 230°C, on the other hand, the effective convective heat transfer between circulating heated air and skin/sheathing of the leading edge of the wing is provided only at a sufficient path length, passable heated air. Great widespread use obtained the system of the shallow channels, arranged/located along airfoil chord (as, for instance, in the deicer on the wing of the aircraft of Tu-164 and An-24, described above). It should be noted that the depth of channels exerts a considerable effect on the effectiveness of heat exchange - for example, an increase in the depth of channels from 3 to 5 mm¹ involved an increase in the quantity of heat from source by 20-250/o for guaranteeing the prescribed/assigned temperature of the surface (best heat exchange is accomplished in the channels whose length is considerably more than their perimeter).

FOOTNOTE 1. In one of concrete/specific/actual constructions.

ENDFOOTNOTE.

Designer is forced to search for the optimum version of system, since a great increase in the length of channels although improves heat exchange, in this case the overall requirement for a quantity of heat increases. Increases also the structural weight. For the wing of

average sizes by this optimum version is the heating in section 12-150/o of airfoil chord.

Thermoelectric system considerably more easily provides the heating of the surface of small sizes/dimensions.

Construction/design of system and its reliability in operation.

The major advantage of the air-heat continuous system, as already mentioned, in simplicity of its construction/design. This advantage when, on the aircraft, sufficient sources of hot air are present, is frequently decisive when selecting of the type of system.

The failure probability of the air-heat system is very low.

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Failure is feasible only with the failure of the mechanisms of the opening of shutters/valves whose quantity in continuous system is small. However, the damages of the conduits/manifolds, channels of corrugation and dual skin/sheathing (which could seriously upset the operation of system) appear extremely rarely ¹.

FOOTNOTE ¹. In practice are known the cases of destruction of

conduits/manifolds and other damages; however, their reasons were usually the use/application of material, not answering the requirements. ENDFOOTNOTE.

Thermoelectric system with its longitudinal and transverse thermal "knives", generators of alternating (or constant) current, programmers, contactors and so forth is more complicated, its failure is more probable. System requires stricter control/check. As shown in experiment of operation, possibility of hot spots, the damage of electrical heating elements/cells and main leads are not completely removed. It is considered that for a thermoelectric system of the type "Spraymat", in spite of the presence of protective coating, essential shortcoming is the possibility of damaging a heating layer as a result of erosion from rain and hail in flight at high rates.

The production of thermoelectric system in comparison with the air-heat is also more complicated and labor-consuming.

However, the thermoelectric system of cyclic action allows, as already mentioned, to restrict zone heating approximately by section, that constitutes 80% or all chord. This has important value, especially when designer on any reasons does not have the capability to arrange zone heating in section by the extent 12-150% chord, which is necessary for the air-heat continuous system. Is not always

also desirable arrangement/position in the leading edge of the wing of the conduits/manifolds of hot air, which occupy considerable place.

Another advantage of the thermoelectric system is the possibility of more precise distribution of supplied energy over the protected surface in accordance with requirements and the possibility of the more precise regulation of necessary temperature depending on the conditions of icing.

It should also be noted that in contrast to the air-heat thermoelectric system of the type "Spraymat" can be established/installed almost on any dimensions and form parts and parts of aircraft.

Effect on flight aircraft quality/fitness ratios.

Air bleed for de-icing system from compressor considerably decreases the thrust of turbojet or the power of turboprop engine, which has especially important value with the operation of engine at maximum and nominal ratings.

For a turbojet engine the decrease of thrust almost is directly proportional to a quantity of selected/taken air. For example, if for

protection from aircraft icing, it is taken by 50/o of quantity of air, expended by engines, then the engine thrust also decreased by approximately 50/o.

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Turboprop engine is more sensitive to shortage of the air entering it, since each percent of the air selected/taken by engine entails a reduction/descent in the power of engine 2-3o/o. In connection with this on aircraft with turboprop engines usually cannot be taken directly from the compressor the quantity of air required for de-icing system, and therefore are applied either with the ejectors (as on the aircraft An-24) or the system with heat exchangers, which to a lesser degree decreases the power of engine.

According to the data of work [37] the maximum quantity of air, which can be selected for protection from icing from turbojet engine, must not exceed 12o/o, from turboprop engine - 7o/o and from turbopiston - 5o/o.

Thermoelectric de-icing system with power take-off to generator from the shaft of the compressor or engine has the definite advantage in this respect. Losses in thrust during selection of one and the same energy content from engine for a thermoelectric system are

considerably less than for air-heat. If we in this case consider that also requirement itself for energy for a cyclic thermoelectric system is much less than for the system, which uses continuous heating by warm air, then this advantage will become even more considerable. According to calculation data the selection of sufficient for protection from the icing of energy content from engine in thermoelectric system decreases the thrust not more than by 10%, i.e., several times is less than in the case of air-heat system 1.

FOOTNOTE 1. Is examined protection from the icing of wing and tail assembly of aircraft with four gas turbine engines, which work in nominal rating. ENDFOOTNOTE.

Losses in the engine thrust make flight aircraft quality/fineness ratios worse and, in the first place, its rate of climb. In connection with this deserves attention safety method from icing, based on the use of the combined air-heat de-icing system with devices/equipment for control of the boundary layer. This method [55], about which already briefly it was communicated in Section 4, makes it possible to decrease the negative effect on the aircraft performance of air bleed from engines.

Is of also interest comparison by the weight of the air-heat and thermoelectric system.

The weight of de-icing systems on old aircraft types with piston engines oscillated in considerable limits depending on type and construction/design of system. For example, on aircraft Boeing B-17 the weight of de-icing system composed altogether only 0.30/o of takeoff weight, on aircraft Douglas DC-6 - 1.10/o, and the aircraft Airspeed "Ambassadeur" - 1.70/o.

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As shows statistics, on contemporary passenger aircraft the weight of de-icing system (designed in accordance with the design conditions accepted) composes 0.6-1c/o of takeoff weight. In this case there is no considerable difference in the all-Union ones between thermoelectric and air-heat systems.

Work [40] gives comparison by the weight of indicated systems for the aircraft with four gas turbine engines, which has wing area 139 m². These data are given below.

From the given data we see that the air-heat system has certain advantage in weight, however, one should take into consideration that in these data the weight of a-c generators is connected in the total

weight of thermoelectric system, while usually on aircraft these generators are used, also, for other users of electric power. Thus, in actuality the weight of thermoelectric system must be somewhat reduced.

Work [40] for the aircraft in question gives also the data about an increase in the specific fuel consumption in working de-icing system. That, for example, during air bleed from the compressors of turbojet engines for the operation of the air-heat system for one hour it is necessary to additionally consume 272 kg of fuel/propellant.

(1) I. Воздушно-тепловая система непрерывного действия

(2) Самолет с турбовинтовыми двигателями	
(3) Вес теплообменников	90 кг (4)
(5) Вес клапанов и органов управления	11 кг (4)
(6) Вес трубопроводов и двойной обшивки:	
(7) в крыле	118 кг (4)
(8) в оперении	100 кг (4)
(9) Общий вес системы	349 кг (4)

(10) Самолет с турбореактивными двигателями
(отбор воздуха от компрессоров)

(5) Вес клапанов и органов управления	32 кг (4)
(11) Вес трубопроводов, двойной обшивки, смешительных камер:	
(7) в крыле	214 кг (4)
(8) в оперении	82 кг (4)
(9) Общий вес системы	318 кг (4)

(12) II. Электротепловая система циклического действия типа «Спреймаг»

(13) Вес четырех генераторов переменного тока по 40 кВт	145 кг (4)
(14) Вес электронагревательных элементов, проводки, органов управления	227 кг (4)
(9) Общий вес системы	372 кг (4)

Key: (1). I. air-heat system of continuous action. (2). Aircraft with turboprop engines. (3). weight of heat exchangers. (4). kg. (5). Weight of valves and controls. (6). Weight of conduits/manifolds and dual skin/sheathing. (7). in wing. (8). in tail assembly. (9). Total weight of system. (10). Aircraft with turbojet engines (air bleed from compressors). (11). weight of conduits/manifolds, dual skin/sheathing, mixing chambers. (12). II. Thermoelectric system of cyclic action of the type "Spraymag". (13). weight of four a-c generators on 40 kw. (14). weight of electrical heating elements/cells, wiring/run, controls.

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For the air-heat system with heat exchangers, established/installed on turboprop aircraft, are required by 180 kg of fuel/propellant, also, for a thermoelectric cyclic system - 110 kg of fuel/propellant.

Maintenance.

The air-heat system with direct air bleed from compressors is simpler in maintenance/servicing. In operation the routine maintenance work along this system usually is reduced to the periodic inspection of the mechanisms of control and control/check and checking of the state of some conduits/manifolds. The service life of the air-heat system with exception of the mechanisms of control and control/check is determined by the service life of the construction of the aircraft.

Servicing the same system with heat exchangers is more complicated, since in operation are required regular inspections and checkings of the state of the heat exchangers, which undergo large thermal stresses.

The maintenance of the thermoelectric system is more labor-consuming than the air-heat one. For this system in operation are necessary the routine inspections and the repairs of the a-c generators, of programmers, checking of electrical heating elements/cells, wire insulation and other works. The service life of system is usually lesser than the service life of the construction of the aircraft.

After feeding/conducting sums to the short comparative examination of two systems, it is possible to draw the conclusion that the thermoelectric de-icing system of cyclic action has advantages in the considerable savings of energy, selected/taken from engines, in considerably smaller negative effect on the engine thrust and of aircraft performance, in the possibility of setting up almost on any parts and parts and possibility of decreasing the size of the warmed zone along airfoil chord.

On the side of the air-heat continuous system - simplicity of construction/design and maintenance/servicing, large reliability, cheapness. It should be noted that during the development of the air-heat systems of periodic action, advantage of thermoelectric system considerably they decrease.

A question about a selection of the type of system always must

be solved concretely/specifically/actually taking into account the available sources of energy and technical flight characteristics of aircraft.

9. Protection from the icing of power plants.

To the de-icing system of the power plants of aircraft (or helicopter) are presented higher requirements, than for the systems of aircraft.

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This is explained by the fact that the flight safety must be provided in any flight conditions; therefore efficiency of power plants must not be seriously reduced, as were not heavy conditions during entire time when aircraft will be located in the zone of icing.

Are known the cases, when icing led to damage or complete service failure of piston and gas turbine engines. For example, on one of the aircraft were discovered the icing of the grid of the throttle case of piston engine, the involved cessation of air intake into engine and its stop (Fig. 3.60). For eliminating this shortcoming it was necessary to considerably enforce the heating of grid.

The axial-flow compressor or gas turbine engine is especially sensitive to icing, since under conditions of icing ice can intensely be formed on intake guide vanes, on the blades of the first series/row of rotor and stator. The icing of these elements of construction/design can begin during several minutes, which can involve the considerable decrease of the power of engine.

Serious can be the cases of damage ice of compressor blades, especially if they are made from aluminum alloys (Fig. 3.61).

Comparatively recently (during January 1960) above the territory of the United States of America suffered catastrophe the passenger turboprop aircraft "Viscount". The committee of the civil aviation of the USA established that the reason for catastrophe was the failure due to the icing of all four engines of aircraft as a result of the overdue start of de-icing system. This case again confirms that the turboprop engines are very sensitive to icing and for them is required highly efficient and reliable anti-icing protection.



Fig. 3.60. Icing of the grid of throttle case on the aircraft of Il-14.

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The special experiments, carried out by the author on the aircraft of An-10, showed that upon the overdue start of de-icing system ice formation on inlet components can seriously upset the operation of engines (up to their complete disconnection). This is explained by the fact that inside engines fall the pieces of ice during their jettisoning from air intakes, in this case occurs the flameout in combustion chambers. It is characteristic that the disturbances/breakdowns in the operation of engine are directly connected with a quantity of ice which can simultaneously be dumped into engine gas-air channel. On the aircraft of An-10 the incidence/impingement into the engine AI-20 of the pieces of ice with a thickness of 10-15 mm and with length, equal to the half of the circumference of air intake, leads to sharp drop in power of engine and decrease of its revolutions to 3-40/o. The incidence/impingement of large-size ice (with a thickness of 20-30 mm) causes the self-disconnecting of engine. The disturbance/breakdown of engine power rating is accompanied by sputtering, knocks and appearance of clouds/clubs/puffs of white smoke on exhaust.

Above has already been noted that large danger for some types of engines represents the icing in the form of the crystals of ice. The engine, given in Fig. 3.62, has almost rectilinear air intake channel, also, in contrast to the engine, depicted on Fig. 3.63, to much smaller degree it undergoes the negative effect of ice crystals. In latter/last airflow pattern changes direction of its motion on 180° near combustion chambers. This in flight in ice clouds can lead to the accumulation of ice crystals in the bent section of air intake.



Fig. 3.61. Damage by ice of the blades of the inlet compressor of engine.

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If by that saving on air intake a layer of ice is broken and falls into compressor, then engine can stop, that also occurred on the aircraft "Britain" whose engines "Proteus" they had diagram [44] indicated. For eliminating this shortcoming on engine "Proteus" it was made the series/row of modifications and, in particular, in combustion chambers were established/installed incandescent candles from platinum alloy for guaranteeing instantaneous repeated start of engine in the case of flameout in combustion chambers. These modifications were carried out after extensive studies and tests, carried out on stand, and also under conditions of crystal icing in tropical areas.

It is characteristic that to this case of engine testing under conditions the "drop" icing showed the completely sufficient effectiveness of de-icing system.

For the protection of engines in the majority of the cases are applied continuous de-icing systems (system antiicing). However, in some aircraft, for example "Viscount" are established/installed thermoelectric cyclic de-icing systems for the air intakes of engines. The cycle of the operation of such systems is selected in such a way as not to allow dangerous ones according to its sizes/dimensions of ice accumulations on the shielded surfaces. The use/application of cyclic de-icing systems on engine is possible only when will be experimentally proved the safety of small ice accumulations on the shielded surfaces of air intakes. A quantity of heat required for protection from the icing of engine can be determined according to the equation of the heat balance (see page 121). As show the calculations (and as this confirms practice), required temperature drops in system for power plant must be somewhat higher than in system for an aircraft.

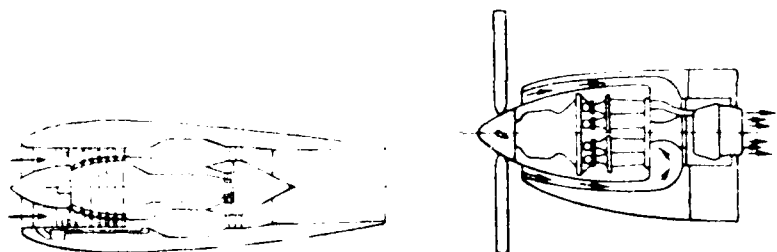


Fig. 3.62. Turbojet engine with the straight/direct entry of air flow.

Fig. 3.63. Turboprop engine with rotation of airflow on 180°.

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It should be noted that in operation the de-icing systems for engines are utilized considerably more frequently than system for wing and a tail assembly. In the duration of the operation of the de-icing system of glider/airframe comprises for a contemporary aircraft with gas turbine engines 3-60/o of flight time¹, then for power plants this numeral reaches 15-20o/o and more.

FOOTNOTE 1. Data are acquired for commercial airplanes of major air lines. ENDFOOTNOTE.

This is explained by the fact that for many aircraft types the

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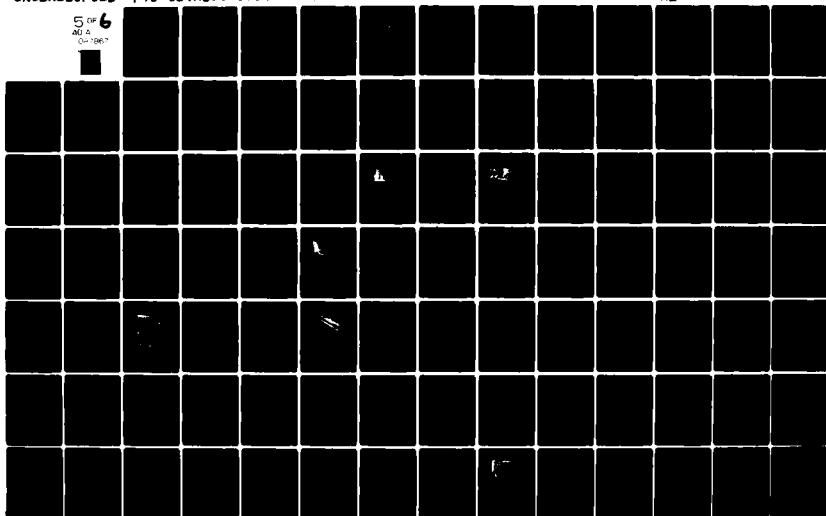
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instruction requires the start of the de-icing system of engines prior to the entry into the cloudiness or any other zone, in which is possible the icing, beginning with the temperature of surrounding air of $+5^{\circ}\text{C}$ even below, while the de-icing system, for example, of wing is included usually after operation signal indicator.

Typical air-heat continuous system for power plant is the de-icing system of the aircraft of Tu-104, in which for protection from the icing of engines RD-3M and air intake channels is utilized the air, selected/taken from the eighth compressor stage. By this air are warmed the nose/leading edge of air intake, the applied spokes of front/leading compressor casing, the fairing about the turbine starter, the exhaust duct of turbine starter and air-fractionating partition/baffle.

For the heating of the blades input guide ring hot air it is selected/taken separately from fifth compressor stage.

The schematic of the de-icing system of engines RD-3M is given in Fig. 3.64.

Hot air for the heating of six applied spokes is supplied from fundamental conduit/manifold 1 through the tee to the collar, installed on upper left spoke. Air is supplied to the channel between

two walls of spoke, welded with spot welding. From upper left spoke hot air enters the neck, from which it is supplied to remaining five spokes and fairings about the turbine starter. Exhaust air is rejected into the air circuit of the engine through openings/apertures in the lower base of five applied spokes. The fairing about the turbine starter consists of two halves with the double walls, between which from base/root to nose/leading edge is passed hot air. Air outlet is accomplished/realized through the opening/aperture in the nose/leading edge of fairing.

Air to the heating of the exhaust duct of turbine starter (cross section A-A) is supplied on conduit/manifold 3 diameters of 25 mm into the cavity, formed by fairing 5 and wall of 6 elbow-shaped tubes of turbine starter.

Air the heating of the noses/leading edges of air-fractionating partition/baffle and air intake enters on conduit/manifold 2 by diameter of 70 mm. The nose/leading edge of air-fractionating partition/baffle (cross section B-B) consists of outer covering by 7, by internal 8, carried out in the form of corrugation, and shield 9. Nose/leading edge shares by wall 10 into two chambers/cameras - A and B.

The hot air, applied into forechamber A, is passed between the shield and the corrugation and through the slot in corrugation along its channels it falls into the rear chamber/camera B, from which through the branch connection it is abstracted/removed into the nose/leading edge of air intake and is rejected in the atmosphere.

Into the nose/leading edge of air intake hot air comes from fundamental conduit/manifold to 2 through the annular recess A (unit I). Further air is passed along the channels of corrugation into cavity B, warming in this case the nose/leading edge of air intake, and it is abstracted/removed in the atmosphere through the special branch connection, arranged/located in the lower part of the air intake.

Air for the heating of the blades the input guide ring (Fig. 3.65), prepared from aluminum alloy, is selected/taken from fifth step/stage and through openings/apertures 1 enters the internal cavity of compressor. Further the air through openings/apertures in the diaphragms of disks 2 is supplied to the front/leading cavity A, from which it enters the heating of the blades through the openings/apertures, situated in the lower pins/journals of blades.

Hot air is passed further along internal duct to the body of blade in leading edge and through the opening/aperture in its upper part it is derived/concluded into the air circuit of engine.

Control of de-icing system - pneumatic. Air from pneumatic system proceeds to valve of control of system, established/installed on panel in the co-pilct. From the tap/crane of control the air is fed/conducted to the taps/cranes of air bleed from left and right-side engine.

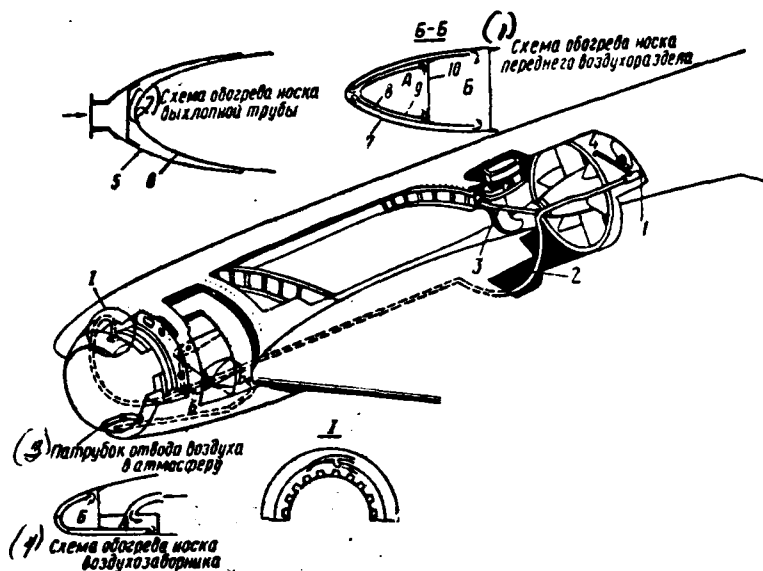


Fig. 3.64. Schematic of the de-icing system of engine RD-3M. 1 - conduit/manifold of the air outlet from engine, 2 - fundamental conduit/manifold, 3 - conduit/manifold of air supply to the exhaust duct of turbine starter, 4 - conduit/manifold of air supply to applied spokes and fairing about the turbine starter, 5 - fairing about the exhaust duct of turbine starter, 6 - wall, 7, 8 - external and lower covering, 9 - shield, 10 - wall.

Key: (1). Diagram of the heating of the nose/leading edge of the forward air fractionator. (2). Schematic of heating of nose/leading edge of exhaust duct. (3). Branch connection of air outlet in the atmosphere. (4). Diagram of heating of nose/leading edge of air intake.

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The de-icing system of engine and engine nacelle they are autonomous for each engine.

The expenditure of air for the heating of the air intake of engine at the height/altitude of 1000 m and indicated airspeeds 400 km/h is 1250 kg/h, to the heating of air-fractionating partition/baffle - approximately/exemplarily 350 kg/h. With an increase in altitude of flight to 8000 m the expenditures/consumptions fall respectively to 950 and 260 kg/h.

De-icing system of such type (it is analogous with system for the wing of the aircraft of Tu-104) makes it possible to increase the air flow rate and, consequently, also to raise the effectiveness of its action with an increase in engine power rating. So, the increase in the engine revolutions, which corresponds to an increase in the flight speed from 400 to 600 km/h according to instrument, leads to the increase of the expenditure of air for the nose/leading edge of air intake on 100 kg/h and to an increase in the temperature drops on nose/leading edge on the average on 12°C.

The dependence of the expenditure of air for the heating of the nose/leading edge of air intake on engine power rating is given in Fig. 3.66.

The de-icing system of engines D-20P and air intakes on the aircraft of Tu-124 also is air-heat with the use of hot air, selected/taken from the compressors of engines.

For the heating of the nose/leading edge of air intake the air is selected/taken through the check valve from the fourth or eighth compressor stages of engine. With the revolutions of the rotor of the second cascade/stage of compressor of above 9200 r/min the air is selected/taken through conduit/manifold 1 (Fig. 3.67) from the cavity of housing after the fourth step/stage of the second cascade/stage, while with revolutions it is below 9200 r/min - through conduit/manifold 2 of the collector/receptacle, located in the rear end of the external cavity or combustion chamber, i.e., after the eighth step/stage of the second cascade/stage of compressor.

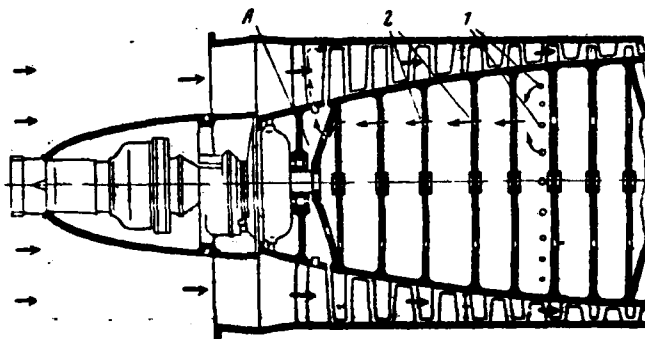


Fig. 3.65. Schematic of the heating of the blades the input guide ring of engine RD-3M.

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Switching air bleed from the fourth or eighth compressor stage is accomplished/realized by automatically throttle plate 3.

The flow chart of air in the nose/leading edge of air intake is analogous to the aircraft of Tu-104.

The engine cowlings, strut or intake housing and the steel blades the input guide ring (VNA) of the first cascade/stage of compressor are warmed by the hot air, selected/taken from interlabyrinth cavity A of the eighth step/stage of the second cascade/stage of compressor and ejected in ejector 4. In ejector is supplied the air,

selected/taken directly after the eighth step/stage. Further air on two heat-insulated conduits/manifolds 5 through the openings/apertures of four collars of intake housing is fed/conducted into annular recess B, formed by the rim of intake housing and by outer ring of VNA. From annular recess B the part of the air on openings/apertures in the rim of intake housing enters longitudinal cavities 6 of its struts. In passing by cavity in struts and warming their leading edges, air enters the heating of the fairing, which has double walls, after which through openings/apertures it emerges into the air circuit of compressor.

Another part of the air from annular recess B through openings/apertures in the pins/journals of external blade tips enters longitudinal channels 7, warming leading edges, and through slots in the root cross section of blades it emerges into the air circuit of compressor. Four cheeks of intake housing are additionally warmed by oil, applied from centrifugal air separator.

The start of system is produced by the discovery/opening the check valves, arranged/located in engine nacelle. Valve control - electrical, toggle switch of control it is established/installed on the instrument panel of the co-pilot.

For the protection of engine AI-20 and air intakes of the

aircraft of An-10 is utilized hot air, selected/taken from compressors. The schematic diagram of de-icing system is given in Fig. 3.68.

The air, selected/taken from two collars of the tenth compressor stage, is forwarded through taps/cranes 3, controlled by electrical mechanisms 2, into two conduits/manifolds 6 and 8, on which further it is fed/conducted to the nose/leading edge of the air intake of engine and oil cooler, and also to the blades of input guide ring.

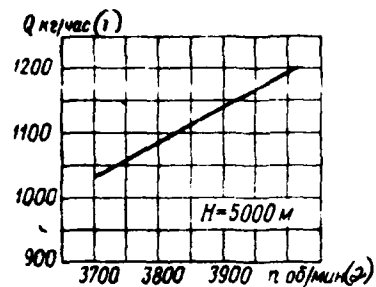


Fig. 3.66. Dependence of the expenditure of air for the heating of the nose/leading edge of the air intake on engine speed RD-3M.

Key: (1). kg/h. (2). r/min.

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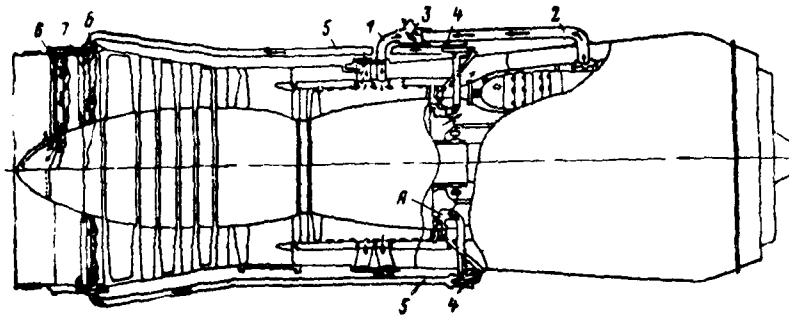


Fig. 3.67. Schematic of de-icing system of engine D-20P. 1 - air extraction manifold from the fourth step/stage of the second cascade/stage of compressor, 2 - air extraction manifold from the eighth step/stage of the second cascade/stage of compressor, 3 - throttle shutter/valve, 4 - ejectors, 5 - conduits/manifolds of air supply to the heating of blades of VNA, struts of intake housing and cowl of engine, 6 - cavity in the strut of intake housing, 7 - longitudinal channel in blade of VNA.

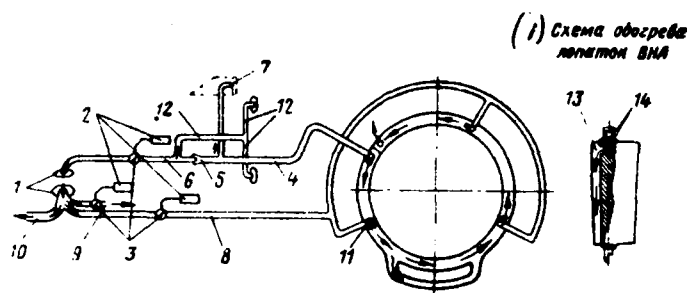


Fig. 3.68. Schematic diagram of the de-icing system of engine and air intakes of engine AI-20. 1 - air bleed from the compressor of engine, 2 - electrical mechanisms of the drive of taps/cranes, 3 - taps/cranes, 4 - conduit/manifold of fundamental air supply into the nose/leading edge of the air intake of engine, 5 - ejector, 6 - conduit/manifold of air supply to the heating of blades of VNA, of air intake of engine and generator, 7 - conduit/manifold of air supply to the heating of the air intake of generator ventilation, 8 - conduit/manifold of supplementary air supply into the nose/leading edge of the air intake of engine, 9 - conduit/manifold of air supply for the blowout of oil cooler, 10 - conduit/manifold of air supply into the system of conditioning, 11 - nozzle (38 mm), 12 - conduit/manifold of air supply to the heating of blades of VNA, 13 - internal cavity of blade, 14 - opening/aperture in pin/journal for the supply of hot air.

Key: (1). Schematic of the heating of blades of VNA.

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Air for heating of the nose/leading edge of air intake is fed/conducted on one fundamental conduit/manifold by 6 through ejector 5 (in diameter of nozzle 12 mm) and to the second - to supplementary 8, which goes from general/common/total aircraft main line.

Air supply from fundamental conduit/manifold is produced through openings in the diaphragm of the nose/leading edge of air intake, and supplementary conduit/manifold - through three nozzles with a diameter of 8 mm, arranged/located evenly in circumference. Hot air is passed on the annular chamber, formed by skin/sheathing of nose/leading edge and by diaphragm, obtains the supplementary portions of the hot air through nozzles it emerges into the space under the cowl through the opening/aperture in diaphragm.

To the heating of the blades of input guide ring, prepared from steel, the air enters on conduit/manifold 12 and further through two diametrically opposite openings/apertures in frontal crankcase. Then on special openings/apertures 14 in head pivots of blades of VNA air passes into internal cavity 13, warming the leading edges of blades,

after which it emerges into the air circuit of engine.

The de-icing system of engine encompasses also permanent heating by oil of the edges/fins of frontal crankcase, and also hot-air heating of the air intake of generator ventilation 7.

10. Protection from the icing of the cockpit windows of crew.

The important value for guaranteeing the normal IFR flight, and especially during landing, has reliable and highly efficient protection from the icing of the cockpit windows of the pilots.

On contemporary aircraft the de-icing system of glasses, as a rule, continuous thermoelectric. However, the setting up of the electrically heated glasses does not eliminate the supplementary use/application and other means: the system of the heating of glasses by hot air, feed system to anti-icing liquid.

Calorific requirement for protection from the icing of glasses of cockpit comprises less than 10/o of the total quantity of heat, consumed by entire de-icing system of aircraft.

The electrically heated glasses consist usually of two (sometimes - three) hardened/tempered silica glass - external (cover)

and internal, glued/cemented between themselves. Between glasses are placed electrical heating element/cell and two special temperature-sensing devices (thermistors). Heating element has two conclusions, which are connected to the electric power supply sources. The thermistors one of which working, and the other - spare, are intended for automatic control the temperatures of heating glass within the prescribed/assigned limits.

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As electrical heating element/cell is utilized the transparent current-conducting layer (glasses with wire electrical heating element/cell did not find propagation because of the diffraction effect, which impeded survey/coverage during landing under nighttime conditions with the use of ground-based lighting sources).

As a rule, internal glasses of aircraft from pressurized cabins obtain satisfaction thicker than cover glass. So, on the aircraft of Tu-104 internal glass in cockpit has a thickness of 15 mm, and external - 4 mm.

Before cementing both glasses (external and is internal) pass mechanical and heat treatment.

The current-conducting film will be deposited from inside of cover glass by aerosol method.

The resistance of the current-conducting layer and, consequently, also the power, consumed by electrical heating element/cell, are determined by the sizes/dimensions of the area of a layer and by its thickness.

To two opposite sides of the current-conducting layer by special method are stuck metallic power buses. The uniformity of heating is provided by the appropriate location of current-tap busbars/tires and by change in the specific resistance of film.

For feed/supply of the electrically heated glasses is applied alternating current by voltage 190-250 V with frequency of 400 Hz.

Fig. 3.69 gives the electrical circuit of the heating of glass with feed/supply from the aircraft electrical wiring system of alternating current [5].

The start of the heating of glass is accomplished/realized by switch 3, which supplies feed/supply from the busbar/tire of direct current to the automatic machine of heating 4.

The automatic machine of heating controls/guides contactor 2, including or including with its aid the electric power supply of heating element upon reaching of the specific temperature of glass (usually 30-40°C). The control winding of contactor is connected with contact D of automatic machine, and thermistor 5, that uses by temperature-sensing device, with contacts BK of the automatic machine of heating.

Feed/supply of glass is accomplished/realized from the busbar/tire of alternating single-phase current with voltage 115 V with frequency of 400 Hz through the raising autotransformer.

During the operation of the electrically heated glasses with high specific powers of heating (on the order of 0.5-0.8 W/cm²) at low temperatures of surrounding air as a result of the high rate of heating appear large thermal stresses.

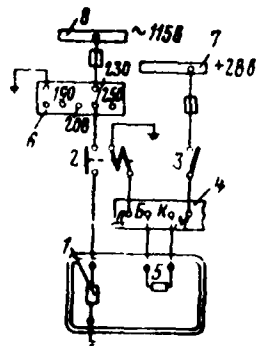


Fig. 3.69. Diagram of the electrical heating of glass. 1 - heating element, 2 - contactor, 3 - switch, 4 - automatic machine of heating, 5 - thermistor, 6 - autotransformer, 7 - power bus of direct current, 8 - power bus of alternating current.

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This leads to the failure of glasses and, therefore, to a reduction/descent in their resource/lifetime.

For a decrease in the velocity of heating is applied stepped feed/supply of glasses on voltage or according to the heating temperature.

With the two-stage voltage or supply of glasses the start of first stage (with low voltage) provides the specific power of heating

to 30-40% smaller in comparison with the second step/stage. The rate of heating in this case is decreased 1.5-2 times.

Another method of stepped feed/supply of the electrically heated glasses during their operation on the earth/ground under winter conditions is the limitation of operating temperature of heating in comparison with the temperature of the external surface of glass with the normal operation of the automatic machine of heating. For this in parallel to the thermistor of glass is established/installed the controlling resistance, which accomplishes/realizes the step connection of heating which decreases operating temperature of heating glass by the earth/ground.

In flight through the limit switch of squeezed landing-gear position (as this carried out on the aircraft of Tu-124) occurs the automatic changeover to the initial temperature of the adjustment of glass (i.e., is disconnected the controlling resistance).

On foreign aircraft at present are applied the glasses of four types: neza, electrapane, triplex (with gold film) and serracoat [62].

In glasses neza and electrapane as the current-conducting layer is utilized the thin oxide film, applied to glass at high

temperature. Both coatings are almost achromatic, although they somewhat decrease the quantity of light let pass by them.

Film triplex, in contrast to the first two coatings, is the combination of gold film with the film of bismuth, plotted/applied to glass by pulverization/atomization in vacuum.

Serracoat is also the metallic coating, applied by its evaporation in vacuum. This coating is applicable both for silica glass and for organic, in contrast to the first three types of coatings. In coating of serracoat are excluded the places, which call hot spots or destruction of glass. Serracoat and gold film triplex are characterized by larger electrical conductivity than neza and electrapane, and therefore can work with lower voltage feed/supplies. Both coatings have insignificant coloration.

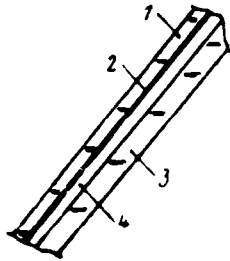


Fig. 3.70. Cross section of glass of the cockpit canopy with coating of serracoat. 1 - skin from semihardened glass with a thickness of 4.83 mm, 2 - coating serracoat, 3 - interior layer from the annealed glass with a thickness of 9.65 mm, 4 - interlayer polyvinyl - butyral with a thickness of 6.35 mm.

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All four coatings are sensitive to mechanical effects; therefore is applied sandwich construction with purpose of protection from damages. This provides also the electro-insulation of coating.

Are given below calculation data, borrowed from work [62] about a quantity of heat, required for warning of icing and misting of glasses (Fig. 3.70) of the lamp/canopy of the flight deck of turboprop aircraft at cruising speed 555 km/h.

Initial data.

Temperature of the external surface (minimum) ... 1.7°C.

Temperature of air in the flight deck (minimum) ... 18.3°C.

The dew point in the flight deck (maximum) ... 29.5°C.

Results of calculation.

Quantity of heat, applied to the external surface of glass ... 5690
kcal/h·m².

Coating temperature ... 34.5°C.

Temperature of the internal surface of glass ... 29.5°C.

Quantity of heat, applied to the internal surface of glass ... 110
kcal/h·m².

Total quantity of heat, applied to glass ... 5800 kcal/h·m².

Required specific expenditure/consumption of electric power ...
0.66 W/cm².

It should be noted that the heat consumption for warming the icing of glasses is considerably more than for warming their misting. Glass consists of three layers: internal, external and intermediate.

The tests, carried out by the administration of civil aviation in the USA showed that for glass for protection from destruction with the cases possible in operation or the incidence/impingement in it of birds the temperature of an layer intermediate in it must be 32.3-45°C. This temperature due to elastic state provides the maximum energy absorption of impact/shock. Is reached it at coating temperature by 34.5°C. It is expedient coating temperature to establish by several degrees than higher indicated, which gives more than guarantees for the protection of glass of the cockpit canopy.

11. Ice-indicating equipment.

As already mentioned by the necessary condition for the effective operation of the de-icing systems of engines, and also the thermoelectric de-icing systems of cyclic action is their timely start. This requirement can be satisfied by setting up on the aircraft of the highly sensitive signal indicators, reliable in action, which inform pilot about the beginning of icing. Such signal

indicators are necessary also for correct and rapid evaluation by the pilot of flight conditions, which has less important value, than the timely start of de-icing system.

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To ice-indicating equipment is presented the series/row of the requirements, basic from which are the following:

1. Reliability of operation, i.e., the transmission/delivery of signal under any conditions of the icing both drop and crystal, in all flight conditions and the impossibility of transmitting the spurious signal.

2. Minimum triggering time, which characterizes instrument sensitivity up to initial moment of icing.

It is desirable so that the instrument would put out signal somewhat earlier than that moment/torque when ice accumulation on the shielded parts can be discovered already visually.

3. Possibility to note with signals it began, end/lead and icing intensity, and it is also desirable so that signal indicator would automatically control/guide operation of de-icing system from such

parameters as temperature of surrounding air and rate of formation of ice.

4. Small overall dimensions and weight.

5. Warning sensor must not substantially affect aerodynamic aircraft quality/fineness ratios.

Ice-indicating equipment can work on one of the following principles.

a) determination in the atmosphere of the supercooled drops of water (or the crystals of ice) at temperatures lower than 0°C ;

b) the direct recording of the formation/education of a layer of ice at sensor.

First type signal indicators are based on the measurement of the indirect values, for example, of electrical resistance or conductivity, heat emission, etc. and for them compulsorily is required the measurement of the temperature of surrounding air, in order to exclude false readings at positive temperatures of surrounding air. Some signal indicators of this type according to their operating principle do not distinguish the supercooled drops of

water from the crystals of ice or snow. Advantage of such type of signal indicators is their rapid reaction at the initial moment of icing.

Second type signal indicators are based on the direct effect of a layer of ice to sensor. This possibility is their advantage, since signals are put out only if actually/really begins icing. A shortcoming in the signal indicators of this type - inertness large in comparison with the first type, in connection with the fact that for ice formation is required the specific time.

Second type simplest in construction/design signal indicator is standard sight indicator of the icing (see Fig. 2.6).

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The second type includes also the signal indicators of the pneumatic and mechanical action, which obtained at present considerable propagation, in spite of the number of the shortcomings which are inherent in them, from which most essential is the delay in the transmission/delivery of the signal of icing.

The existing series signal indicators do not satisfy the completely given requirements. In the majority of the cases they not

automatic, do not measure the rate of the increase of ice and do not record form icing.

In recent years were only developed the sufficiently reliable signal indicators, which made it possible carry out on some aircraft automatic breaking of de-icing system.

Let us examine the device/equipment of several types of the ice-indicating equipment, which are applied on contemporary aircraft and helicopters.

Series Soviet signal indicator SO-4A puts out signals about beginning and end/lead of the icing of the elements of the construction/design of engine. The pneumatic operating principle of instrument is based on the use of elastic properties of sensing element - the metallic corrugated diaphragm, that closes electrical contacts with the decrease of aerodynamic pressure, caused by closing with the icing of openings/apertures in the air intake of signal indicator.

The schematic pneumatic-electrical diagram of signal indicator is represented in Fig. 3.71.

Signal indicator is differential manometer with two hermetically

sealed chambers/cameras 1 and 2, divided by the membrane/diaphragm. Chambers/cameras communicate by discharging jet 3.

Chamber/camera 1 receives the dynamic pressure of the incident airflow through openings/apertures 4 in the air intake of instrument, chamber/camera 2 - static pressure. During the operation of engine (in the presence of velocity head) in the chambers/cameras of differential manometer is established/installed pressure difference, which deflects the membrane/diaphragm and which breaks contact.

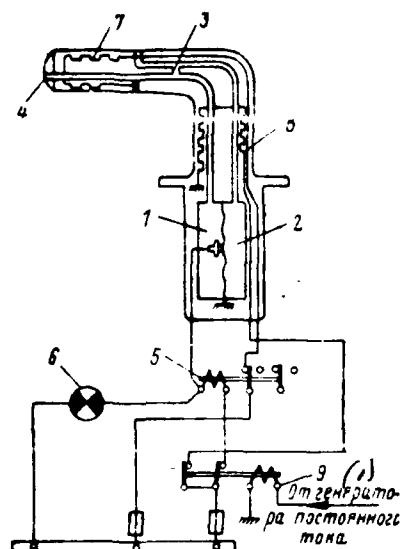


Fig. 3.71. Pneumo-electrical diagram of ice-indicating equipment SO-4A for an engine. 1 - chamber/camera of dynamic pressure, 2 - chamber/camera of static pressure, 3 - discharging jet, 4 - opening/aperture of the dynamic head, 5 - relay, 6 - indicator lamp, 7 - heater of the nose/leading edge of sensor, 8 - heater of the elbow of sensor, 9 - relay.

Key: (1). From direct-current generator.

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Under conditions the icing of opening/aperture 4 seal themselves by the film of ice, pressure in chambers/cameras 1 and 2 through

discharging jet 3 is equalized, and the membrane/diaphragm, returning to initial position, closes contacts. In this case operates/wears electromagnetic relay 5, which feeds indicator lamp 6 and heater of sensor 7.

As a result of heating sensor ice melts, is reduced drop/jump pressure in chambers/cameras, the contacts of manometer are broken, turning off/disconnecting through the electromagnetic relay indicator lamp and heater of the sensor of signal indicator.

Upon the appearance of the first signal of icing the pilot must by hand include/connect de-icing system and disconnect it after the cessation of the supply of signal.

The elbow of signal indicator for a preservation from ice formation is warmed. The heating element of 8 elbows of signal indicator obtains the feed/supply through relay 9, which operates/wears upon reaching by the engine of the specific number of revolutions and in the presence of signal about icing.

As an example of mechanical signal indicator serves signal indicator with the rotating cylinder of the firm of Nepir' [37], [42], established/installed on some new English aircraft, in particular, on VC-10.

Signal indicator consists of unheated cylinder and blade-like scraper (Fig. 3.72). Cylinder has cuts and it slowly rotates by the electric motor, spring-mounted so that it can be turned to small angle.

The clearance between the scraper and the cylinder comprises the approximately/exemplarily tenth of millimeter.

With the icing between the scraper and the rotating cylinder is created the friction, moment/torque from which is transmitted to the housing of electric motor, the latter is pulled around axis/axle and closes the contact, which includes the signaling system.



Fig. 3.71. Signal indicator with the rotating cylinder.

Key: (1). Scraper. (2). Direction of airflow. (3). Cylinder.

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After the cessation of icing the electric motor under spring effect returns to initial position and contact it is broken.

Instrument is sufficiently sensitive and does not need heating. In another variety of instrument the electric motor is fastened/strengthened motionlessly, and is moved scraper.

The radioactive ice-indicating equipment RIO-2A is intended for supplying the signal about the entry of aircraft into the zone of

icing and continuous signaling about the continuous process of icing.

The operating principle of instrument is based on the absorption of the beta-radiation of radioactive source by a layer of ice, which builds up on external cylindrical stub.

Signal indicator consists of sensor, electronic component and delay unit.

The general view of the signal indicator of the Rio-2A, the device/equipment of sensor and schematic electrical diagram are depicted on Fig. 3.73, 3.74, 3.75.

The sensor of the signal indicator (see Fig. 3.74) consists of hollow housing 1 with cover/cap 2, flanged for setting up in cut-out on the outer covering of aircraft, cylindrical stub 6 by length 60 mm, the housing pressed in cover/cap, and the counter of radioactive radiation 7, arranged/located in housing.

In the upper part of the stub is placed the hermetically sealed source of β beta-radiations by the activity of 0.5 millicurie. In the cover/cap of housing above the counter of radioactive radiation milled out slit-shaped window 3.



Fig. 3.73. Ice-indicating equipment of the FIC-2A.

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The rod of sensor is warmed by alternating electric current by the voltage 115 V, which passes on special winding by 5 of the constantan wire with a diameter of 0.15 mm. The specific power of heating - 7 W/cm².

Electronic component of the FIC-2A-1 (see Fig. 3.75) encompasses the power supply unit, which consists of two rectifiers and power transformer, the integrating chain/network, amplifier stage and individual point relay.

The grid voltage of tube L1, proportional to a number of the

impulses/momenta/pulses entering, is provided by the integrating chain/network, which consists of heating element 3 and resistance to 7. In order to avoid the false responses of instrument due to the fluctuation of the flow of beta particles, time constant of the integrating chain/network are selected sufficiently large (about 2 s).

In the anode circuit of tube L1 is connected R1, during operation of which through contacts is supplied the signal into delay unit and to the winding by the relay R3, which includes heating element 3. The circuit of the winding of this relay contains consecutively/serially one additional pair of contacts 15, extended, when aircraft stands on the earth/ground. This pair of contacts protects from burnout the heating element of prong, since heat removal without blowout is insufficient.

The delay unit of the R10-28-2 is intended for the transformation of periodic signal into continuous upon the entry of aircraft into the zone of icing, and also for jettisoning ice from the surface of the external stub or sensor.

As the basis of delay unit is assumed the principle of the expansion of input pulse with the aid of an electronic circuit of the type univibrator.

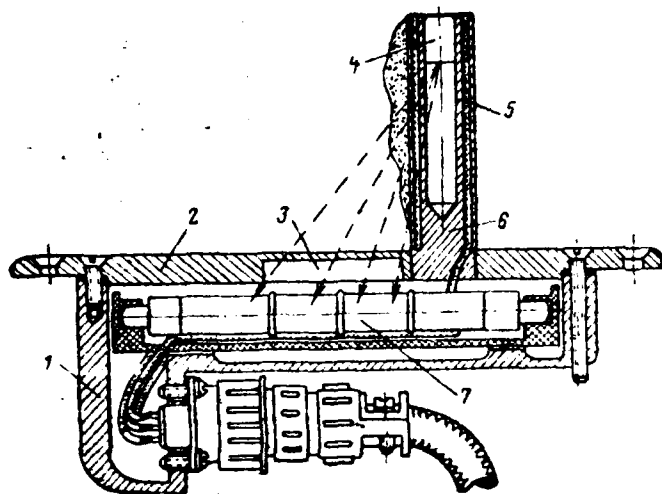


Fig. 3.74. Construction/design of the sensor of the signal indicator of the RI0-2A.

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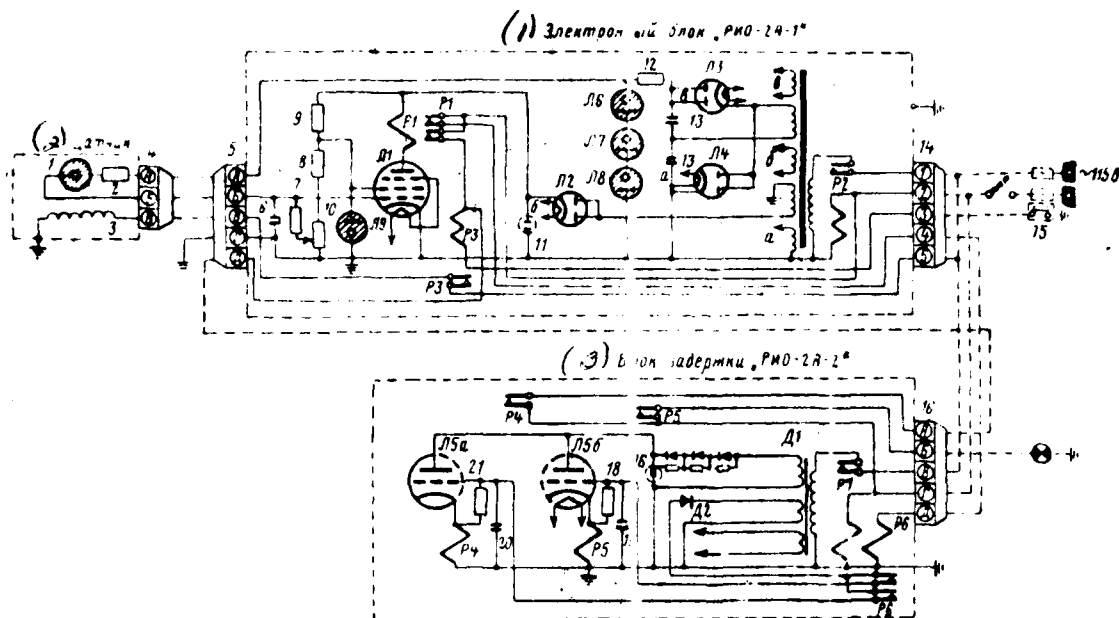


Fig. 3.75. Diagram of ice-indicating equipment of RMO-2A. 1 - control of β -radiations, 2, 7, 8, 9, 10, 12, 18, 21 - resistance, 3 - heating element, 4, 5, 14, 16 - plug-type connectors, 6, 11, 13, 19, 20 - capacitors/condensers, 15 - contact.

Key: (1). Electronic component. (2). Sensor. (3). Delay unit.

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After inclusion and warm-up of instrument in it is established/installed the following state: the potentials of the

grids of tubes L5 and L5b approximately/exemplarily are equalized with the potentials of the corresponding cathodes - both tubes conduct current; therefore relay R4, R5 disconnect their normally closed contacts.

One of these contacts disconnects the bulb of the signaling of the zone of icing, by another - heating element of external stub.

With the icing of the stub of sensor the flow of the beta particles, which irradiate counter 1, weakens, which leads to the decrease of a number of coming impulses/momenta/pulses from counter on integrating chain/network 6 and 7 and to a reduction/descent in the negative potential on control electrode of tube L1.

At certain value of a voltage drop in the anode circuit of tube L1 flows the current and on relay R6 will be given the fast signal in the form of impulse/momentum/pulse by voltage 27 V with duration of 2-4 s.

Through the contacts of this relay is supplied the grid voltage of both tubes L5a and L5b, which locks them. Since relay R4 and R5 prove to be de-energized, their contacts are closed and supply voltage on the bulb of signaling the zones of icing and heating element of the external stub or sensor. At this time occurs the

charging of capacitors/condensers (20, 19), circuital tubes L5a and L5b. After the distance of ice from the stub of sensor in the section of the source of beta-radiation and cessation of the supply of input pulse the contacts of relay R6 and R7 are broken, and begins discharging capacitors/condensers 19, 20 through resistance to 18 and winding by relay R5 in the channel of the pulse delay of the zone of icing and through resistance of 21, winding by relay R4 in the channel of the pulse delay of the heating of stub. The current of overcharging creates on the resistance 18, 21 drop/jump in the voltages, which holds tubes in the closed state.

During flight in the zone of icing the described process is repeated in such a way that delayed pulses, supplied to the bulb of the signaling of the zone of icing, overlap.

Feed/supply of the tubes of delay unit is accomplished/realized from the rectifier, carried out on semiconductor diodes.

Instrument sensitivity, i.e., the thickness of ice on the stub of the sensor, with which occurs the operation of signal indicator, is within the limits of 1 mm.

The ice-indicating equipment of the **RIO-2A** is made in series and is established/installed on the aircraft of Tu-114, Tu-124 and An-24.

Ice-indicating equipment SB 1 is related to the first type of the signal indicators, which operate/work in the presence in the atmosphere of the supercooled drops of water at temperature of air of lower than zero.

FOOTNOTE 1. Signal indicator is developed by M. F. Belov and K. M. Belov. ENDFOOTNOTE.

A signal indicator of the type SB is established/installed on the series helicopter of Mi-4 and is intended for the power feed of signal to pilot about beginning and cessation of icing.

The schematic diagram of instrument is given in Fig. 3.76.

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As the basis of the operation of instrument is assumed the electrical conductivity of ice, which settles on the surface of sensor. During settling on the surface of the sensor of ice occurs closing/shorting the slip rings of sensor, to one of which is conducted/supplied the voltage +27 V, and to another, through the contacts of relay RP-4, is connected control electrode of thyatron.

TG1-0.1/1.3. During the supplying to the grid of the thyatron of positive voltage the instrument operates/wears and are included the heating of sensor and indicator lamp on flap in cockpit. The heating of sensor is intended for the periodic jettiscning of ice from the surface of sensor. windings of polar relay RP-4 together with thermistor TS and resistors R3 and R4 form the short-circuited bridge.

At positive temperatures on the sensor of icing the relationship/ratio of coil currents of polar relay RP-4 is such, that the contact L is extended.

At temperatures to the surface of the sensor of the ice-indicating equipment or 0°C or below drag-rise characteristics of thermistor changes the relationship/ratio of coil currents of polar relay in such a way that the contact L is closed and connects up control electrode of thyatron TG1-01/1.3 to the slip ring of the sensor of ice-indicating equipment. This connection of the grid of thyatron excludes the possibility of operating the instrument during flights into rain, i.e., at positive temperatures when occurs closing/shorting the slip rings of sensor by the film of water.

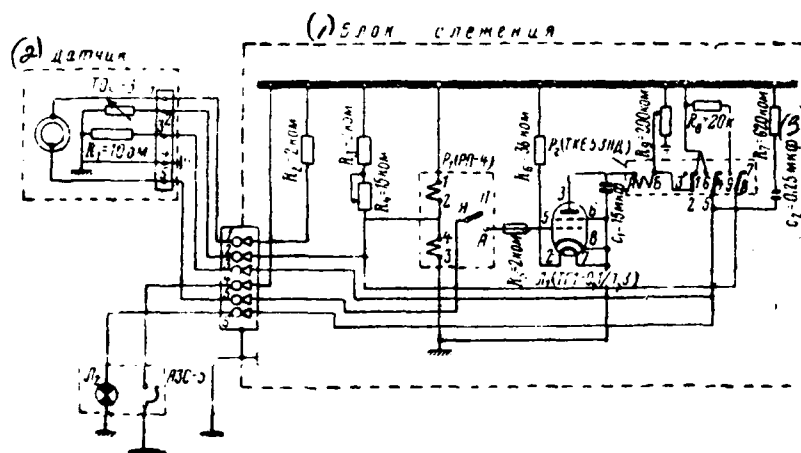


Fig. 3.76. Schematic diagram of the ice-indicating equipment of the type SB.

Key: (1). Tracking unit. (2). Sensor. (3). μF .

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Because of electrical conductivity of ice layer deposited on the surface of the sensor of the ice-indicating equipment, control electrode of thyatron obtains the positive potential, sufficient for the triggering/opening of thyatron. In order not to render inoperable thyatron during the random short circuits between the rings of sensor, voltage from onboard net to sensor is fed/conducted through resistance of R_2 and to the grid of the thyatron through

resistance of R5.

In the anode circuit of thyatron is connected the winding of power relay R2. With the course of the current through this winding occurs the operation of relay R2, as a result of which through its contacts is supplied the voltage +27 V on the heating of the surface of the sensor of icing R1 and on the tube L2, which signals about the presence of icing.

During heating of the surface of sensor occurs the slight melting and the removal of the deposited layer of ice, heating thermistor and change in its resistance. Heating must be disconnected upon reaching by the temperature-sensing device of 30-40°C, which is provided due to the start of resistance of R8 through the contacts of relay R2 in parallel to resistance of R3 and R4. Value R8 is selected during the control of instrument. Potentiometer R9 serves for the control of voltage in the anode circuit of thyatron with the connected relay R2.

Since with direct/constant voltage on the anode of thyatron L1 the removal/taking positive potential with grid does not lead to the extinction of thyatron, the latter works in the relaxation mode/conditions RC, resistance which is the effective resistance of winding by relay R2, but by capacity/capacitance - a

capacitor/condenser C1. This mode/conditions of the operation of instrument is characteristic by the oscillation/vibration of voltage on the anode of thyatron from +27 V to 0. Relaxation oscillations in thyatron appear only in the presence of positive potential on control electrode of thyatron and cease during its removal/taking on with decrease in the anode voltage of up to the voltage of extinction. The frequency of voltage in the circuit of the anode is selected considerably higher than the frequency of the mechanical of the anchor of relay TKE53PD now is eliminated the possibility of the spontaneous explosion of its electrical circuit.

Structurally/constructurally ice-indicating equipment consists of two parts: sensor of icing and tracking unit.



Fig. 3.77. Sensor of a signal indicator of the type SB.

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The sensor of icing depending on site of installation on aircraft or helicopter can be carried out in different structural/design versions. The fundamental elements/cells of sensor are the slip rings, established/installed on framework/body from insulation, heating element, arranged/located within framework/body, and temperature-sensing device. As temperature-sensing device serves the thermistor of the type TOS-3, mounted in the framework/body of the sensor of signal indicator.

Sensor, carried out in the form of of stub or profile/airfoil (Fig. 3.77), are established/installed aboard, perpendicularly to

airflow.

The tracking unit consists of base/root, on which is mounted the diagram of instrument and jacket. base/root is established/installed on bracket to four rubber fenderings. The jacket of ice-indicating equipment is fastened to base/root with three screws/propellers.

12. Special features/peculiarities of protection from the icing of helicopters.

For a helicopter the greatest danger represents the icing of the blades/vanes of the carrying and tail rotors.

Ice accumulation on the blades/vanes of rotor conducts to a considerable increase in the drag and lift convergence. An increase in the resistance of the blades/vanes of tail rotor with its icing so significantly does not affect the helicopter characteristics.

However, as a result of the low sizes/dimensions of profile/airfoil the increase of ice on its blades/vanes occurs more intensely.

The icing of helicopter is developed in an increase in the vibrations, the incidence/drop in the engine revolutions and the onset as speaking pilots, "drivings" of knob/stick. In this case an increase in the revolutions to previous value does not lead to the

restoration/reduction of the lift of screw/propeller. Especially sharply icing affects the light helicopters.

Below, table 14 gives the data [61], which show in what measure with icing, without the start of de-icing system, it is necessary to increase the power of engine in order to support the initial revolutions of the screw/propeller (investigations were conducted under bench conditions while hovering, water content 0.3 g/m^3 , temperature of surrounding air or -7°C).

Table 14. Data about the engine power increase necessary with icing on helicopter depending on the time, which passed after the beginning of icing.

(1) Продолжительность обледенения сек	(2) Увеличение мощности %
20	6
40	10
60	16

Key: (1). Duration of icing s. (2). Increase in power.

Table 15.

(1) Продолжительность обледенения мин	(2) Увеличение мощности двигателя в % при температуре окружающего воздуха	
	-5° C	-15° C
1	0,4	0,6
2	1,5	2,5
3	3,0	5,0
5	8,0	(3) 11,0
10	23,0	около 30,0

Key: (1). Duration of icing min. (2). Increase of power of engine in o/o at temperature of surrounding air. (3). about.

With further icing, in spite of an increase in the power of engine, the lift of helicopter was decreased, and it lost altitude.

The effect of icing on helicopter characteristics to a considerable degree depends on the temperature of surrounding air. Table 15 gives the results of the bench investigations, carried out on the helicopter of Mi-4 under conditions of the icing, created artificially with water content of approximately 0.2 g/m^3 . From these data it is evident that at temperature of air of -15°C is required a larger increase in the power of engine, than at -5°C , since the section of the icing of propeller blades changes in dependence on temperature and flight conditions.

At high temperatures of air on propeller blade they ice up only in the section of blade/vane to the specific maximum radius. The values of this radius for a leading edge, upper and blade faces are different (Fig. 3.78).

At low temperatures, on the order of -10°C it is below, rotor blades of the helicopter of Mi-4 ice up all over length, moreover the intensity of the increase of ice on leading edge is proportional to a radius. In level flight the picture of ice formation changes. So in the section of blade/vane to 0.2-0.3 of radius (i.e. in the limits of the zone of reverse/inverse flow) ice builds up it is weakly and

formed only on strip by the width, which corresponds to the small percentage of blade chord. Further in a radius the rate of the increase of ice increases and toward the end of the blade/vane approaches the icing intensity while hovering of helicopter (Fig. 3.79).

The form of a layer of ice on the nose/leading edge of blade/vane depends mainly on the temperature of surrounding air and can change along the length of blade/vane from tapered to channeled/grooved and to horn-shaped (with leading edge free from ice) Fig. 3.80. Fig. 3.81 gives different forms of ice, photographed on the blades of the propeller of helicopter after flight under conditions of natural icing.

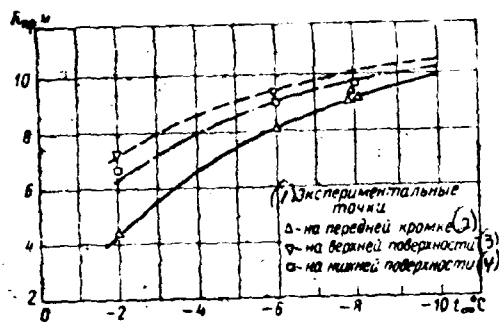


Fig. 3.78. The maximum radius of the icing of the helicopter rotor blades of Mi-4.

Key: (1). Experimental points. (2). on leading edge. (3). on upper surface. (4). on lower surface.

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In one of the experimental flights while hovering under conditions of the supercooled fog ($n=2400$ r/min, boost pressure 1100 mm Hg, temperatures of surrounding air of -5°C) the icing of the blades/vanes of the rotor of the helicopter of Mi-4 had the following character: from the root of blade/vane to rib No. 20 was formed tapered ice, from rib No. 20 in section in long approximately two meters ice had channeled/grooved form and further horn-shaped with free leading edge. From rib No. 40 and to end/lead on the blade/vane of ice accumulations it was not.

For the protection of the screw/propeller of helicopter from icing can be used the following methods: air-heat, liquid, thermoelectric and physicochemical (use of coatings, which decrease the cohesive force of ice with the shielded surface).

The air-heat continuous de-icing system did not have extensive application for the protection of the screws/propellers of helicopters due to the complexity of distributing warm air along

blade/vane. Furthermore, another difficulty for a system of the type indicated is the problem of "barrier" ice, which appears as a result of runoff and freezing of water after the warmed zone. A question becomes complicated also by the fact that during the manufacture of blade/vane from light alloy, the temperature of air at the inlet into root of the blade/vane must be limited from strength considerations.

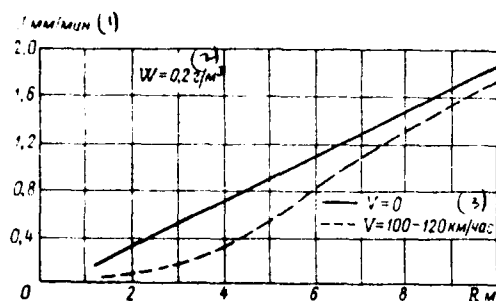


Fig. 3.79. Intensity of the increase of ice on the leading edge along the length of blade/vane.

Key: (1). мм/min. (2). г/см³. (3). км/h.

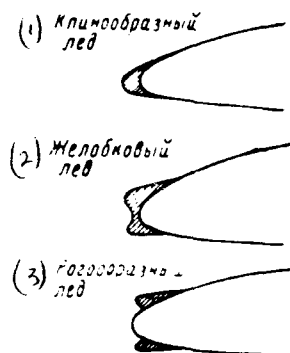


Fig. 3.80. Forms of ice, which is formed on blades/vanes of helicopter.

Key: (1). Wedge-shaped ice. (2). Channeled ice. (3). Horn-shaped ice.

Even less let us use for the blades of the propellers of helicopters safety method from icing with the aid of pneumatic protectors, that as protectors with work systems sharply change the profile/airfoil of the cross section of propeller blades, which is extremely undesirable. Furthermore, appears the danger in rapid erosion from rain of material of protectors at blade tip.

An attempt at the protection of helicopter screws/propellers with the aid of the hydrophobic coating as which was used teflon, was not crowned by success.



Fig. 3.81. Ice formation on the helicopter rotor blades of Mi-8 in flight with switched off de-icing system. a) the tapered form of ice, b) the channelled/grooved form of ice, c) the transition/transition of the channelled/grooved form of ice into horn-shaped.

In spite of its simplicity, method it proved to be insufficient to effective ones, although under laboratory conditions were achieved/reached sufficiently good results [61]. Splitting ice occurred upon reaching of the thickness of ice 5 mm and more at the tip of blade and 8-10 mm on low radii of blade/vane and it is very uneven.

During the use/application of hydrophobic coating it is also difficult to ensure sufficient strength and resistance to abrasion of the latter.

On contemporary helicopters is applied mainly liquid and thermoelectric de-icing systems.

The use of a liquid de-icing system is connected with a number of difficulties. In connection with the fact that to liquid in channels within blade/vane operate the large centrifugal forces, appears the problem of the even distribution of liquid on blade/vane. Furthermore, the effectiveness of the action of system to large degree depends on the opportuneness of its activation. With the delay of the inclusion the liquid washes in ice narrow grooves and ensues/escapes/flows out on them, while on remaining surface remains

a considerable quantity of ice (Fig. 3.82).

Other shortcomings in the liquid system - need for having sufficiently large reserve of liquid the aboard and limited time of action of deicer. Latter/last shortcoming is aggravated by the requirement to include system prior to the entry into cloudiness, which is sometimes connected with the useless expenditure of liquid due to the absence in the clouds of icing.



Fig. 3.82. Action of liquid de-icing system upon overdue start.

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Therefore for the effective and economical work of liquid deicer it is important to have on helicopter highly sensitive and reliable ice-indicating equipment.

There are two methods of supply of de-icing liquid to the shielded surface of blades/vanes - through the series/row of the separate openings/apertures, situated along leading blade edge and through porous metal skin/sheathing (in this case inside blade/van is introduced not the liquid, but the froth [58], which because of low density is insignificantly subjected to the action of centrifugal

forces).

System with openings/apertures is simpler, more easily it is assembled and does not require supply to the blade/vane of air for foaming.

Furthermore, during the use/application of a system with froth is not excluded the possibility of the forcing of porous metal at blade tip from the abrasive effect of solid particles. However, deicer with froth has essential advantage in the considerably more uniform and more economical distribution of liquid according to blade/vane ¹.

FOOTNOTE ¹. The liquid de-icing system of this diagram was developed by the English firm TKS by researchers S. Khal'bert, D. Tenner et al.
ENDFOOTNOTE.

The schematic of the distributor of liquid on the blade/vane of helicopter is depicted in Fig. 3.83, borrowed from work [58]. Blade/vane has two channels: one is arranged/located directly under external porous skin/sheathing, in it is introduced the foam liquid, by another it is located under the first and it is isolated from it by porous diaphragm. In second channel periodically is supplied the compressed air, which penetrates through the porous distributive wall

the first channel and displaces it to surface.

An example of the use/application of liquid de-icing system of screws/propellers with distribution of the liquid through openings/apertures serve the helicopters of Mi-4, Mi-1 and "Wessex" of the firm Westland helicopter.

The de-icing system of the screws/propellers of helicopter Mi-4 consists of tank by the capacity/capacitance of 58 ℓ , pump with electric motor, filter, conduits/manifolds and control displays of the operation of system (Fig. 3.84).

Supply to anti-icing liquid from tank 1 in the blade/vane of the carrying and tail rotors is accomplished/realized with the aid of centrifugal type pump 5, put to action by the electric motor of direct current 6.

Electric motor can work on two modes/conditions: preliminary - with fluid flow rate of approximately 1.5 ℓ /min and increased, with expenditure/consumption approximately 2.2 ℓ /min.

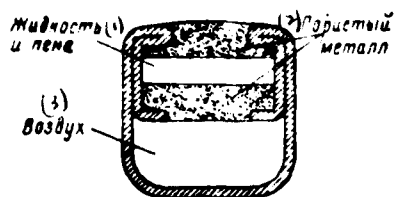


Fig. 3.83. Diagram of distribution of liquid on the blade/vane of helicopter.

Key: (1). Liquid and frctn. (2). Porous metal. (3). Air.

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Electric motor in the first mode/conditions works in the case of the preliminary inclusion of the system before the entry into cloudiness, and also with weak icing. Under more severe conditions the system is switched to the increased operating mode. The switch of the mode of operation of electric motor is arranged/located in cockpit.

Pump is connected by conduit/manifold with tank, forming suction line. The output of liquid from pump occurs through the reverse/inverse valve to which with the inoperative pump it does not make it possible for liquid to escape/ensue into the main line of conduits/manifolds. After the cessation of supply it leaves liquid in conduits/manifolds, giving thereby the possibility to avoid the time

loss to the filling of main line by liquid.

Anti-icing liquid after the pump through gauze filter 7 and throttle valve 9, which controls general/common/total expenditure/consumption, enters the forcing main line. Its conduit/manifold has a tee from which two tubes go to collector-distributors 11 and 13 of main and tail rotors.

From collector-distributor or rotor liquid on flexible hoses under the action of centrifugal forces it stumbles in the blade/vein of rotor.

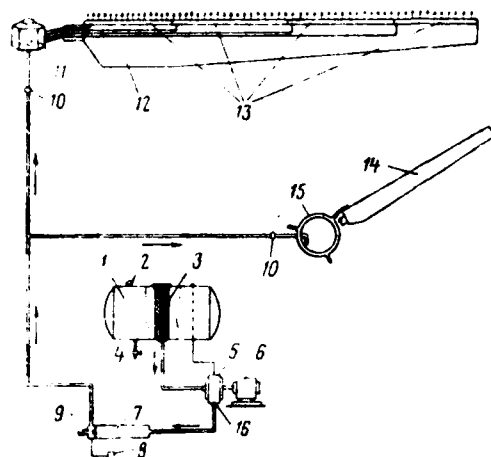


Fig. 3.84. Schematic diagram of the de-icing system of the screws/propellers of the helicopter of Mi-4. 1 - tank, 2 - drain, 3 - gauge, 4 - drain, 5 - pump STSN-1, 6 - electric motor, 7 - filter, 8 - pressure indicator SD-16A, 9 - throttle valve, 10 - washer with metering hole, 11 - collector/receptacle of rotor, 12 - blade/vane of rotor, 13 - section of blade/vane, 14 - blade/vane of tail rotor, 15 - collector/receptacle of tail rotor, 16 - check valve.

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Each blade/vane consists of four sections. The liquid, conducted/supplied to the forward section of each section, falls into the slot, formed by the tipping or leading blade edge and by special

shape. From slot the liquid escape/ensues to the leading blade edge through the opening/aperture with a diameter of 0.8 mm, arranged/located along the length of blade/vane in two series/rows in checkered order at a distance of 3 mm upward and downward from leading edge. Pitch of holes is 30 mm. The liquid, which ensues to leading blade edge, rescues by air flow over upper and blade faces.

The anti-icing liquid, which enters the collector-distributor of tail rotor, is rejected by centrifugal forces through three tubes into the receivers of the blades/vanes.

From the receivers the fluid proceeds into pockets, and then into grooves of blades,, from which under the action of centrifugal forces and air flow it spills over surface, washing it.

As anti-icing liquid is utilized distilled alcohol.

The English firm Westland helicopter also developed the liquid de-icing system of blades/vanes for the helicopter "Wessex".

Fig. 3.85 gives the cross section of blade/vane with liquid deicer.

Blade/vane is shielded at length from 0.3 of radius to end/leaf. De-icer is divided along the length of blade/vane in 4 sections to which is fed/conducted the liquid, which consists of 90o/o of alcohol and 10o/o of glycerin.

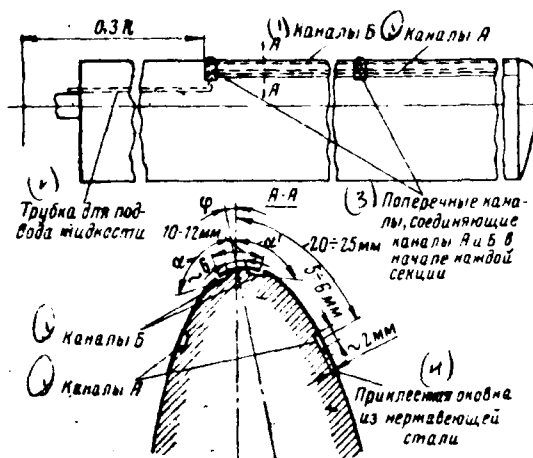


Fig. 3.85. Construction/design of the experimental liquid delivery system of helicopter rotor "Wessex".

Key: (1). Channels. (2). Tube for supply of liquid. (3). Transverse channels, which connect channels A and B in the beginning of each section. (4). Sticking tip made of stainless steel.

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On the surface of the nose/leading edge of blade/vane are milled longitudinal grooves. On the nose/leading edge of blade/vane on an arc 40-50 mm on arc is stuck the tipping made of the stainless steel. Thus are created the longitudinal channels A and B, which are connected between themselves by the transverse channels of small

cross section in the beginning of each section. Along channels A the liquid is distributed on sections. Channels B are the fundamental channels of the deicer on which the liquid is fed/conducted to the openings/apertures with a diameter of 0.7-0.8 mm, staggered with space 25-30 mm.

Channels B and, consequently, also openings/apertures are shifted to lower side so that at the average/mean blade angle openings/apertures would be arranged/located symmetrically relative to the actual aerodynamic line or total stagnation on the nose/leading edge of blade/vane. In this case is considered blade twist.

The rear walls of channels B have such an inclination/slope, that at any value of angle φ the angles α and α' remain blunt relative to the plane of the rotation of blade/vane. Therefore is provided the uniform discharge of liquid from openings/apertures.

Tail rotor has the analogous construction/design of deicer, but altogether only with one section at the beginning of which is fed/conducted the liquid.

The described construction of deicer eliminates the leakage of liquid from under tipping and provides uniform washability of loading

edge and more or less uniform washability of the remaining surface of tipping for the zone of the location of openings/apertures.

Nominal fluid flow rate - about 0.5 l/min to one blade/vane of rotor.

Thermoelectric the method of the protection of the blades/vanes of helicopters from icing is most effective and it makes it possible to in the best way ensure the distribution of required power of the heating of blade/vane with the retention/preservation/maintaining of the aerodynamic shape of profile/airfoil [56].

The thermoelectric de-icing system of cyclic action for protection from the icing of the helicopter rotor blades was for the first time developed and it was established/installed on the Soviet helicopter of Mi-6.

On the English series helicopters Westland "Wessex" so is established/installed at present the thermoelectric de-icing system of screws/propellers of the type "Spraymat" of the firm of Napier. Heating elements are supplied as finished article, and with the aid of simple device by the compressed air they adhere on blades/vanes after the preliminary treatment of the surface of the latter. Gluing is produced by heating, for which special heaters are introduced.

inside gently longeron/spar.

Work [32] gives the results of the investigations, carried out by the English firm Napir by choice of the optimum parameters of the de-icing system: location of heating elements on the surface of blade/vane, sizes/dimensions of the shielded zone, energy consumption, the time of heating and cooling the surface.

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There are two methods of separation of the shielded surface of propeller blade in the section: on spread/scope or along chord. Both methods on their effectiveness of action are approximately/exemplarily identical.

The separation of blade/vane into heating elements along the length makes it possible to more easily change the scope/coverage along chord along blade/vane, and to also provide the more rapid and more complete jettisoning of ice. In this case the appearing dynamic asymmetry is less than during jettisoning of ice by long sections along chord. Shortcoming in this method - more complicated construction/design of heating elements and large quantity of current-conducting busbars.

The separation of blade/vane into long zones along chord makes it possible to more simply arrange elements/cells and power buses of each warmed zone. The formation of "barrier" ice after unheated zone from latter/last heating elements can be brought to the minimum by timing of heating section. However, a system of such type requires somewhat greater power in view of the fact that ice must be chipped up all over length of blade/vane. The formation of "barrier" ice is reduced, since the ice is thrown off consecutively - from the leading edge back along the chord.

For determination of the necessary zone heating along chord for the varied conditions for flight was calculated and determined experimentally the zone of the deposit of cloud drops. For the helicopter "Wessex" the shielded zone encompasses 100% of chord over upper surface and 25% of chord - on lower (from leading edge) and stretches from 1/3 radii to the end/lead (as noted above, root of the blade/vane in the zone of reverse/inverse flow in section to 1/3 radii can remain unprotected).

Investigations showed that for decreasing the asymmetric dropping of ice and for preventing the formation of barrier ice it is necessary to apply the very larger specific powers with least possible time of heating. The required specific power of heating is the function of the temperature of surrounding air and to change along the length of blade/vane. On the graph (Fig. 3.86), borrowed from work [12], they are given the dependence of the specific power

of the heating of blade/vane over its length on the temperature of surrounding air.

The selection of the time or on position of sections, or cooling time, depends on icing intensity. This time must be so as not to allow dangerous formation of ice which can lead to an excessive increase in the resistance of blade/vane and a reduction/descent in its lift effectiveness, or to the damage of glider/airframe by the large pieces of jettisonable ice.

Jettisoning ice must be produced fast enough and completely for preventing the imbalance rotor (with asymmetric dropping).

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The heating time for each radius of blade/vane depends on specific power and temperature of surrounding air.

A number of cyclically warmed sections limited by maximum permissible ice accumulation during cycle depends on the source power of the current and the specific power used. With an increase in the specific power the overall requirement for energy is decreased.

Because of kinetic heating, and also centrifugal and aerodynamic

forces, the time, necessary for the dropping of ice under certain conditions and at identical specific power of heating, is changed along blade/vane, being less at end/lead than in root. Under the condition for the simultaneous jettisoning of ice all over length of blade/vane it is desirable the specific power of heating to change from the minimum at end/lead to maximum in the root of blade/vane.

Tail rotor, as already mentioned, pain was sensitive to imbalance and therefore it must be warmed or continuously or cyclic time must be reduced not less than three times in comparison with fly rotor.

For simplification in the deicer (in particular, for decreasing a number slip rings) it is expedient to consider tail rotor as one cyclic zone. In this case ice from blades/vanes will be dumped simultaneously.

The overall diagram of the de-icing system of helicopter with coating of the type "Spraymat" or the firm of Nepir is shown in Fig. 3.87.

For the cyclic thermoelectric system of helicopter, just as for an aircraft, it is desirable to change the cyclic recurrence of the work of deicer in dependence on the conditions of icing. It is

necessary that on the blades/vanes would be plotted a sufficient quantity of ice for its complete removal.

During jettisoning of ice of insufficient thickness will occur its thawing and formation of barrier ice.

Ideal would be system with automatic regulation of the mode of operation of deicer, what requires reliable instruments - thermometer and rate meter of icing.

The selection of electrical power supply is produced in dependence on that, such as requirement - on weight or simplicity of construction/design - must be satisfied first of all.

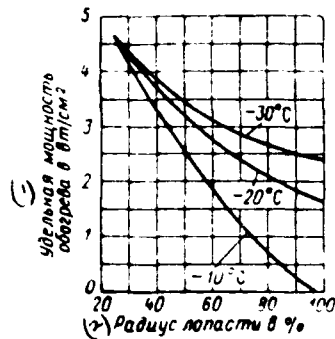


Fig. 3.86. Dependence of the specific power of the heating of blade/vane on the temperature of surrounding air.

Key: (1). The specific power of heating in W/cm². (2). Radius of blade/vane in o/o.

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From the point of view of simplicity of constructions/designs, best is the system of direct current, but its weight is too great in comparison with equivalent alternating-current system. The firm Nopir considers the best power supply the generator of three-phase alternating current.

For cyclic feed/supply of heaters is required the series/row of slip rings. For the purpose of the decrease of their number by firm

Nepir was developed the system of switching, decreasing a number of the slip rings of lift rotor to three. As switch serves the rotating contactor with drive from electric motor. In system must be provided timing of heating ("working" time) within certain limits with the retention/preservation/maintaining of constant/invariable cyclic recurrence.

As has already been indicated, the electrically heated coatings are made separately and then they are established/installed on propeller blades. Coatings preliminarily are balanced and are weighed.

Coating of type Spraymat consists of foil, fundamental insulating layer, heating elements, obtained via the atomization of metal, busbars/tires and upper insulating layer. For preventing the erosion from rain and mechanical damages leading edge has special protective coating (Fig. 3.88). Tail piece of the blade/vane at length approximately/exemplarily $1/3$ has metallic coating from nickel foil. Root of the blade/vane (approximately/exemplarily $2/3$) is shielded by coating Starguard, mentioned above.

The blades/vanes of tail rotor as a result of high rotational speeds must be shielded by metal coating on entire spread/scope.

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The weight of the experimental thermoelectric de-icing system of helicopter "Wessex" is equal to 107 kg, including generator with voltage regulator and rate meter of icing.

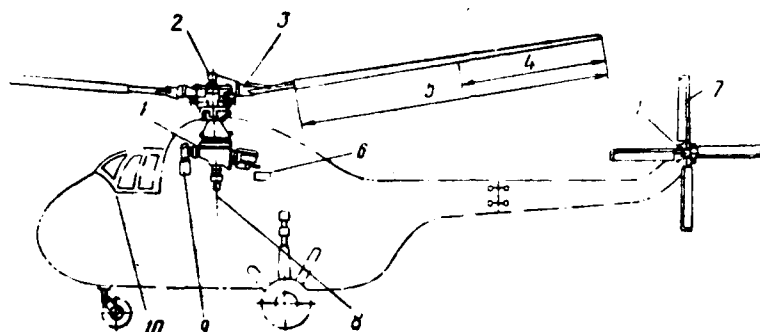


Fig. 3.87. Overall diagram of the de-icing system of helicopter with coating of the type Spraymat. 1 - slip rings, 2 - cyclic switch, 3 - plug-type connector; 4 - anti-erosion tape (40% of blade/vane), 5 - coating the type Spraymat (88% of blade/vane), 6 - monitor and contactor, 7 - coating the type Spraymat, 8 - electric power supply through the main shaft, 9 - a-c generator and fan, 10 - switch on the control panel of pilot.

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It should be noted that the weight of the electrically heated coatings can be partially or completely compensated by the equivalent decrease of the counterweights to the nose section of the blade/vane. Furthermore, heavy equipment as a-c generator, voltage regulator, contactor, etc. can be fulfilled by detachable for the exception/elimination of supplementary weight during the flights of helicopter in areas where usually are not encountered conditions of

icing.

The de-icing system of the helicopter of Mi-6 encompasses the thermoelectric system of the cyclic action of blades/vanes the carrying and tail rotors and the permanent electrical heating of the noses/leading edges of the air intakes of engines and glasses of flight deck.

Spinner and struts of intake compressor casing constantly warm themselves by hot oil, but the leading edges of blades of inlet guiding device - by the hot air, selected/taken from engine.

For feed/supply of electrical heaters is applied the three-phase alternating current with the frequency of 400 Hz, voltage 208 V, developed two generators in power on 90 kW each.

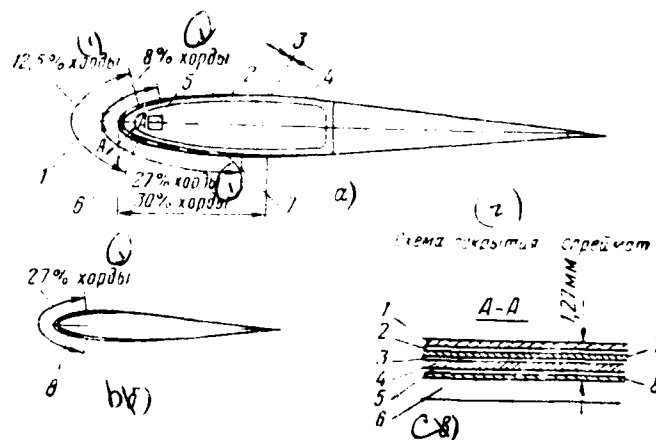


Fig. 3.88. Schematic of the design of blades/vanes for the carrying and tail rotors of helicopters. a) the cross section of the blade/vane of rotor, b) the cross section of the blade/vane of tail rotor. 1 - tape of protection from erosion, 2 - copper foil, 3 - coating with a thickness of 0.254-0.305 mm, 4 - aerodynamic duct/contour of the profile/airfoil, 5 - counterweights, 6 - aluminum foil along the length spread/scope to 180° or chord, 7 - six-element zones, 8 - two-element zones, c) the diagram of coating Spraymat. 1 - tape of protection from the erosion with a thickness of 0.305 mm, 2 - layer of the cement with a thickness of 0.127 mm, 3 - element/cell with a thickness of 0.103 mm, 4 - fundamental insulating layer with a thickness of 0.481 mm, 5 - aluminum foil with a thickness of 0.102 mm, 6 - longeron/spar, 7 - upper insulating layer with thickness 0.178 mm, 8 - a layer of the cement with a thickness of 0.076-0.127

mm.

Key: (1). chord. (2). Diagram of coating Spraymat.

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The start of the heating of blades/vanes the carrying and tail rotors is produced by the switch, which allows in dependence on the conditions of icing to establish/install one of the three modes/conditions:

I - heating 20 s, cooling 100 s;

II - heating 40 s, cooling 80 s;

III - heating 60 s, cooling 60 s.

Control of heating and the current feed to heaters of the carrying and tail rotors occurs through slip rings.

On the cover/cap of the housing of current collector of rotor are mounted two contactors of three-phase current, whose control windings are included by programmer.

The heating elements of each blade/vane of rotor are broken in two sections - root and end, approximately with equal resistance. Upon the cyclic inclusion of heater are consecutively/serially included first the root, and then end sections of the heaters of all blades/vanes.

The heating of the blades/vanes of tail rotor is produced also by the start of the contactors whose control winding is included from the same programmer, in this case are cyclically heated the leading edges of two opposite blades/vanes.

Heating elements are arranged/located all over length of blade/vane on the lower and upper surfaces of nose/leading edge to 18.50% of chord. The specific power of the heating of blades/vanes - variable/alternating.

In structural/design sense the heater is an electric heating packet, stuck on the outer covering under pressure 3-5 kgf/cm² at temperature of 150°C.

For the gluing of heaters on the external surface of skin/sheathing of nose/leading edge are selected the cavities with a depth of 0.7-0.8 mm by chemical milling. To the treated thus surface after coating of cement by the thickness of 0.2-0.15 mm and gluing.

of electro-insulation (one layer of the glass cloth, saturated with cement) is stuck the heating element, prepared from the tape of mild stainless steel with a thickness of 0.12-0.3 mm.

Outside heating element/cell is shielded by insulation/isolation from glass cloth and by outer covering from Duralumin with a thickness of 0.4 mm for a root section and from by the which not corrodes flocks thickness of 0.2 mm - for the end section of blade/vane.

Electric wiring feed/supplies of deicer, and also wire/conductor from thermostats are laid on the longeron/spar of blade/vane.

In blade root the wires/conductors are connected to the plug-type connector, established/installed under root fairing.

The deicers of the nose sections of the sections within each section series-connected between themselves by cross connections.

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The permanent heating of the noses/leading edges of the air intakes of engines is accomplished/realized by heaters, whose start is produced by contactor, that operates/works by the start of

general/common/total switch (through the thermostat).

Heating element will be deposited to the internal surface of air intake and consists of several layers of resin of the current-conducting composition.

The heating of glasses or flight deck is accomplished/realized by tape/film heating elements and warm air from electric furnaces.

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Chapter IV.

EFFECT OF ICING ON AERODYNAMIC CHARACTERISTICS AND AIRCRAFT PERFORMANCE.

As we noted, the problem of icing has two sides the first of which consists in negative effect on the operation of power plants, some instruments and equipment, but the second - in a deterioration in flight aircraft quality/fitness ratios.

Let us recall how occurs the flow of air about the wing profile or tail assembly. As a result of the action of the forces of viscosity of air its particles, directly adjacent to wing, are braked, lower the speed of adjacent particles, as a result of which in the wing surface is formed a thin boundary layer of the stagnated air.

The rate in boundary layer varies from zero (on the wing surface) to the local importance of air-stream velocity (on the boundary of boundary layer). The character of motion in boundary layer can be laminar or turbulent. With the laminar particle motion

of air they move over the trajectories, which do not intersect between themselves, and flow bears laminar (hence name - laminar) character. In turbulent boundary layer occur the irregular mixing of the particles of the air, their motion in transverse direction, and flow bears the swirled (turbulent) character. Laminar boundary layer is unstable and easily it passes into turbulent state.

The resistance of any body, streamlined with air, as is known, is made up from the pressure drag, caused by the breakaway of air flow from body, and the frictional resistance, which appears as a result of air friction against body surface. For a contemporary aircraft the latter/last component plays extremely important role. With the turbulent structure of boundary layer the frictional resistance is considerably greater than with laminar.

Flow around of the wing at low angles of attack α (Fig. 4.1a) occurs without the breakaway of air flow 1 , in this case the boundary-layer flow in certain section is usually laminar, and then passes into turbulent state.

Footnote ¹. Let us note that even in the absence of breakaway of the air flow a small pressure resistance will still occur. The cause of this lies in the formation of a vortex wake arising behind the airfoil when the boundary layer of the upper and lower surface of the wing joins.

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The length of laminar section depends on Reynolds number, form of profile/airfoil and from that, to what extent the rough surface of

wing.

The thickness of turbulent boundary layer increases along wing chord more rapid than in laminar. Because of this, the more along the length the section occupies a turbulent layer, the greater the thickness of vortex wake and, therefore, the greater the pressure drag. Thus, with the decrease of the length of laminar section occurs, on one hand, an increase in the frictional resistance, and on the other hand - increase in the pressure drag, which sum causes a sharp increase in the coefficient of profile drag of wing C_{xp} .

The effect of roughness and irregularities of the surface of wing is developed, on one hand, in their internal resistance with another, in the agitation of boundary layer. In this case despite the fact that the internal resistance of roughness can be with their insignificant dimensions very little, nevertheless as a result of contraction of laminar section complete disappearance of boundary layer the profile drag of wing strongly will increase. At the height/altitude of the protuberances/prominences of roughness 20-25 μ their its own resistance can be virtually disregarded/neglected. However, the presence even of such insignificant, it would seem, roughness on an entire wing surface agitates the boundary layer and can, as show calculations, increase the coefficient of profile drag of wing doubly [3].

From the aforesaid it is clear, as will affect the drag of aircraft ice formation on its surface. Even the insignificant icing of any form as a result of its roughness will cause an increase in the drag. This, in particular, it is necessary to bear in mind with the inspection of the surface of the aircraft before the flight when pilots frequently underestimate the danger of the light raid of hoarfrost or frozen snow. Usually with icing as on the earth/ground, that and in air, the thickness of ice, forming on wing (, etc. aircraft components), reaches several millimeters (and sometimes also centimeters), which not only makes the surface of rough, but also leads to the distortion of the enclosures of profile/airfoil.

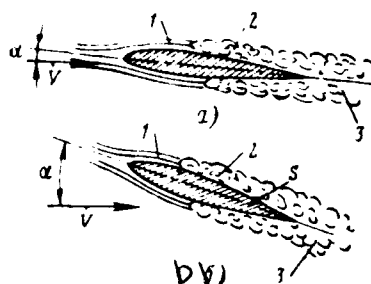


Fig. 4.1. Diagram of the formation/education of boundary layer during flow around of the wing at small (a) and large (b) angles of attack. 1 - laminar layer; 2 - turbulent layer; 3 - vortex/eddy trace, S - separation point of boundary layer.

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Fig. 4.2 gives the photograph of the iced over lower surface of the wing of aircraft Li-2 after experimental flight. This ice formation caused an extremely strong increase in drag.

Wind-tunnel investigations show, how strongly affects the undulation of profile/airfoil drag. For example, when there is present on the wing (with chord 2 m) an undulation, which occupies approximately fourth of wing surface and which has the height of wave 5 mm , coefficient of profile drag, it increases (with Reynolds number, equal to $6 \cdot 10^6$) by 87.5% .

To lift coefficient c_l during flow around of the wing at low angles of the attack (when it does not occur the breakaway of air flow) roughness has small effect. However, as we will see below, these roughness strongly change $c_{l\max}$ wing.

During flow around of the wing at high angles of attack the boundary layer, which increases by thickness along chord, blows away from the wing surface at certain point S (see Fig. 4.1). The reason for this, as is known, it consists in the fact that with an increase in the angles of attack on the upper wing surface increases the rarefaction/evacuation in the forward part of the profile/airfoil and the point of the minimum of pressure is displaced to the wing leading edge. After the minimum of pressure the rarefaction along wing chord rapidly is decreased, i.e., appear high adverse pressure gradients.

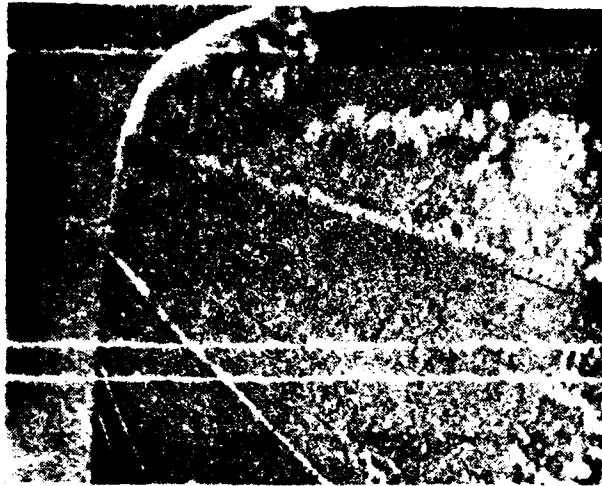


Fig. 4.2. Icing of the lower surface of the wing of aircraft Li-2.

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Boundary-layer air, passing the point of the minimum of pressure, must move to the region of the greater rarefaction/evacuation and not to the region of smaller rarefaction/evacuation, which leads to its braking, appearance of recurrent air circulation near the tail of profile/airfoil and to subsequent boundary-layer separation.

Separation point at first usually is located at trailing wing edge, but with further increase in the angle of attack it is moved forward, to leading edge. The disruption/separation of boundary layer and the adjacent jets of external flow leads to a sharp increase in the air foil drag due to an increase in the pressure drag and lift

convergence.

As is known, with an increase in the angle of attack α lift coefficient C_y at first grows/rises according to the law of straight line. However, at high angles of attack this linear dependence is disrupted, which indicates the begun breakaway of air flow.

At certain critical angle of attack α_{kp} the lift coefficient attains its maximum value. Further increase in the angle of attack causes overall flow separation from wing, rarefaction/evacuation on the upper wing surface rapidly falls, and C_y sharply is decreased.

The dependence of the drag coefficient of wing C_x on the angle of attack α is close to parabolic. With an increase in the angle of attack α it increases and it continues rapidly to grow/rise, also, after critical angle of attack.

From Fig. 4.3 evidently, as changes $C_{y \max}$ wing in dependence on the state of its surface. During coating of the wing surface with carborundum dust $C_{y \max}$ it descends more than 1.7 times and, that also very importantly, simultaneously is decreased the critical angle of attack [3]. Approximately the same effect on the lift effectiveness of wing will show/render the deposit of a thin layer of rough ice.

Decrease C_{max} and C_{up} of the iced over wing depends on the earlier disruption/separation of air flow. During the flow around of the wing air flow they can be the sources of local disruptions/separations even at small angles of attack, which will cause, on one hand, increase in the pressure drag, and with another, it decreases the lift. With an increase in the angle of attack the intense braking of the flow above the wing will enforce recurrent air flows from the tail of profile/airfoil to its forward section. This will lead to the earlier overall disruption/separation of air flow.

Thus, fundamental danger in flight under conditions of icing consists in the approximation/approach of aircraft to separation mode/conditions in the case of ice formation on wing and tail assembly.

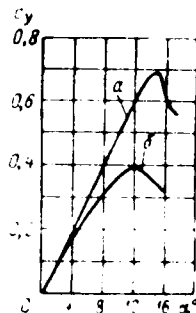


Fig. 4.3. Effect of roughness on the dependence of lift coefficient on angle of attack a) the wing surface flat, b) the wing surface, covered with carborundum dust.

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An increase in the drag and a reduction/descent lift effectiveness will be obviously different in dependence on degree, form and form of icing. Are given below short results of the investigations, carried out by the author on different aircraft types during flights under conditions of natural icing [21], [17], [18].

Investigations were conducted on the special aircraft-flying laboratories which were equipped by the measuring recording equipment. The circuit of investigations consisted in the definition of the level of hazard at the varied conditions of icing both with the worker and in the inoperative de-icing system, in the

determination of the need for the protection of separate aircraft components of icing, in the examination of the special cases of flight, connected with failure of one or several engines, with output at angles of attack, close to critical, with drift to the second circle under conditions of icing, etc.

The work conducted made possible to develop instructions to pilot and recommendation to designer.

The flight characteristics of the iced over aircraft were determined with the fixed/recorded thickness of ice on standard meters. After the growth of ice of the prescribed/assigned thickness and form the aircraft leaves the zone of icing and were fulfilled these or other the maneuvers, necessary for obtaining of the required characteristic.

The determination of field in the various forms of icing was produced by the method of comparison of the rate of climb of the iced over aircraft with the rate of climb of the aircraft, free from ice. The obtained increments in the vertical velocities for each equivalent airspeed made it possible to determine the appropriate increments in the drag coefficient and to construct the dependence $\bar{c}_y = f(c_x)$.

FOOTNOTE 1. This method was proposed in 1952 by M. P. Modilevsky and he was repeatedly applied by the author during processing of the results of investigation. Method is based on the assumption of the equality of the available powers of the iced over and noniced aircraft, which is correct during the guarantee of effective protection from the icing of engines and propellers. ENDFOOTNOTE.

Fig. 4.4 gives the polars of the aircraft of Il-14, obtained by the method indicated with ice formation of the first and second forms in working and switched on de-icing system.

From graph it is evident that the most considerably aerodynamic characteristics of aircraft deteriorate with ice formation of the first form in the switched on de-icing system when icing undergoes the wing of aircraft. In this case the flow of air about the horn-shaped ice flanges on wing causes intense vortex formation, braking and appearance of disruptions/separations, which sharply increases pressure drag and is decreased lift coefficient. With an increase in the angle of attack ice built-up edge causes earlier sharp flow separation on wing, which leads to decrease C_{Lmax} and critical angle of attack.

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Ice of the first form by thickness on standard indicator 35 mm in switched off de-icing system causes sharp shift/shear of polar to the right, increasing its inclination/slope to the axis/axle of abscissas. maximum aerodynamic aircraft quality/fineness ratio descends in this case from 19 (for noniced aircraft) to 11. Drag coefficient increases when $c_y=0,85$ by 700/o.

It is characteristic that these changes occur with the thickness of ice on standard indicator 35 mm, which corresponds altogether only to 16-17 mm on wing (in its middle cross section).

In the working de-icing system when icing undergo only the unprotected aircraft components (center section, engine nacelles, fuselage, struts of antennas, air-pressure heads, etc. - Fig. 4.5), ice formation of the first form or thickness indicated has less considerable, but nevertheless essential effect on polar. Maximum aerodynamic aircraft quality/fineness ratio is decreased to 15, and c_x increases in comparison with the noniced aircraft by 250/o (for value $c_y=0,85$).

The comparison of polars shows that ice of the second form, in spite of doubly large thickness (75 mm), it less considerably makes aerodynamic characteristics worse, than ice of the first form.

In the examination of polar (curve 2) one should take into consideration that a deterioration in the aerodynamic characteristics in this case can occur not only as a result of the icing of the unprotected aircraft components, but also as a result of incomplete distance ice from the wing surface, which sometimes is with accomplishing of flight under conditions of heavy icing.

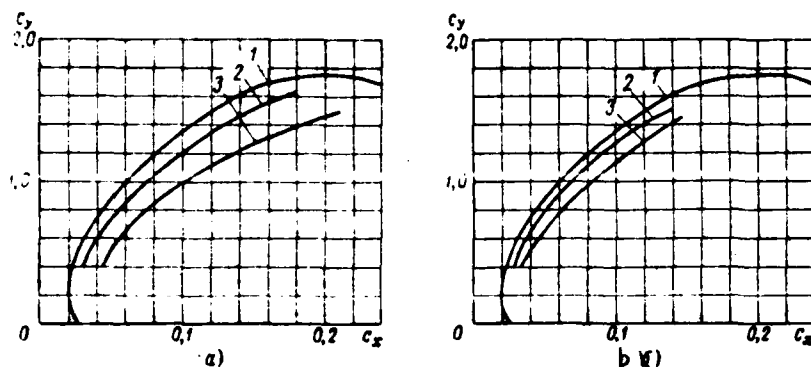


Fig. 4.4. Polars of the iced over aircraft of Il-14. ^{a)} the icing of the first form (thickness of ice on standard indicator 35 mm), b) the icing of the second form (thickness of ice 75 mm). 1 - noniced aircraft, 2 - iced over aircraft in working de-icing system, 3 - iced over aircraft in switched off de-icing system.

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Definite interest from the point of view of the need for the protection of separate aircraft components are of polars with the icing separately of wing, tail assembly and unprotected parts.

Fig. 4.6 gives such polars.

As we see the icing of wing is caused when $C_y=1.0$ an increase in the drag coefficient as, as C_x increases with the icing of all

remaining aircraft components (tail assembly, fuselage, engine nacelles).

On the basis of the obtained polars were constructed the curves of the required and available powers of the aircraft of Il-14 with ice formation of the first form (Fig. 4.7). Curves clearly show to what extent increase the required powers and to what extent descends the maximum speed of aircraft as a result of icing.

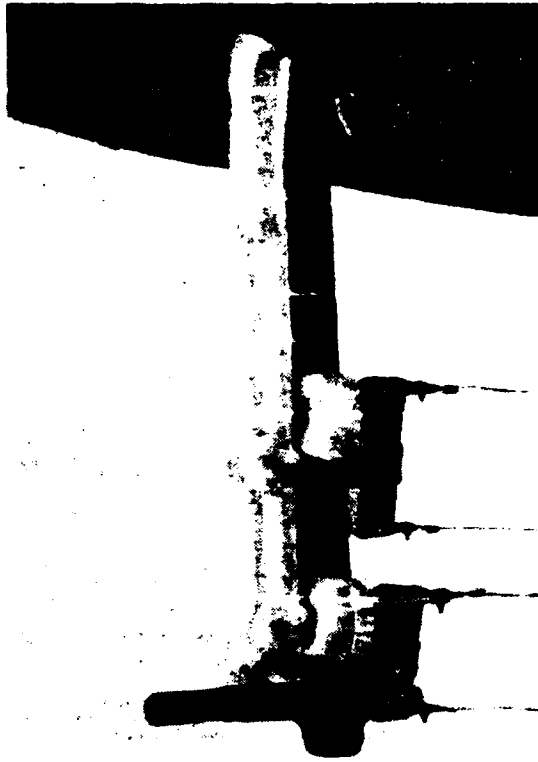


Fig. 4.5. Icing of the unprotected aircraft components. Ice on the strut of air-pressure head.

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Especially sharply the decrease of margin of power affects in flight one engine. The rate of climb of aircraft in this case in working de-icing system (curve 2) is altogether only 0.4 m/s. Obvious that with the somewhat larger thickness of ice margin of power will be

reduced to zero, and conceal by shape, this rate of icing of aircraft will be maximum, with which is feasible the flight on one engine without reduction/descent.

As a result of decreasing the margins of power the rate of climb of the iced over aircraft and its service ceiling descend. The effect of ice of the first and second views of the vertical velocities and the service ceiling of the aircraft of Il-14 in of working and switched off de-icing system it is given in Fig. 4.8.

From the graph (see Fig. 4.8a) it is evident that in the case of ice formation of the first form the icing of the unprotected aircraft components causes decrease of the vertical velocity on 0.8 m/s, and the service ceiling - on 700 m. In switched off de-icing system the vertical velocity descends by 2.6 m/s, and the service ceiling - on 2400 m in comparison with the noniced aircraft.

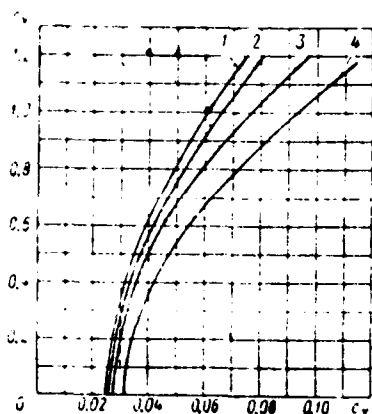


Fig. 4.6.

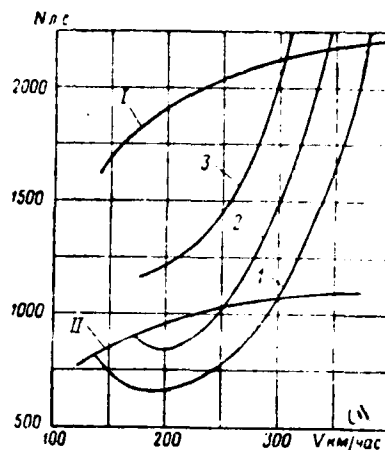


Fig. 4.7.

Fig. 4.6. Polars of aircraft of Il-12 with icing of its separate parts; ice of intermediate form; thickness of ice on standard indicator (42 mm). 1 - noniced aircraft, 2 - iced over aircraft, ice are discarded from wing and stabilizer, 3 - iced over aircraft, ice are discarded from wing, 4 - completely iced over aircraft.

Fig. 4.7. Curves of required and available powers of aircraft of Il-14 (icing of first form, thickness of ice on standard indicator 35 mm). I - work both engines, nominal rating, II - work one engine, nominal rating, 1 - noniced aircraft, 2 - iced-over aircraft in working de-icing system, 3 - iced over aircraft in switched off de-icing system.

Key: (1) - km/h.

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The decrease of rate of climb and respectively service ceiling in the case of ice formation of the second form (thickness on standard indicator 75 mm) is considerably less.

Thus, the given graphs illustrate different effect of two forms of icing on the vertical rates of climb and service ceiling of aircraft.

The decrease of rate of climb as a result of icing negatively affects the possibility of the output of aircraft upward from the zone of icing.

Fig. 4.9 gives the results of determining the rate of climb of the iced over aircraft of Il-14 with drift for the second circle in the case of impossibility set. The origin of coordinates corresponds to the moment/torque of the giving of gas. Those noted to curves the time of the landing gear retracting and flaps (small circles and chain wheels) correspond to moment/torque, when landing gear flaps

are retracted completely.

As can be seen from graph, even in working de-icing system ice formation of the first form (with indicator 70-75 mm thickness on standard seriously makes the rate of climb worse of aircraft with drift to the second circle. with the deflected flaps on 45° after the beginning of the giving of gas the aircraft continues to descend, and it loses altitude (in comparison with noniced aircraft) additionally by 30 m. The distance of the gain of altitude of 50 m increases by approximately 500 m.

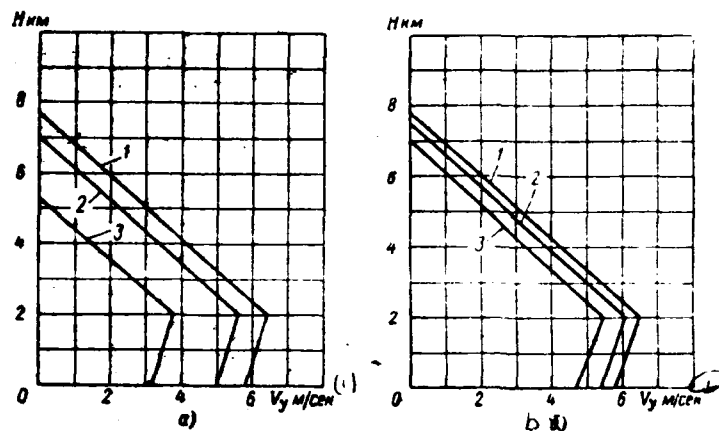


Fig. 4.8. The vertical velocities and the service ceiling of the iced over aircraft. a) the icing of the first form (thickness of ice on standard indicator 35 mm), b) the icing of the second form (thickness of ice 75 mm). 1 - noniced aircraft, 2 - iced over aircraft in working de-icing system, 3 - iced over aircraft in switched off de-icing system.

Key: (1) . m/s.

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It should be noted that the given graphs illustrate the in any way "maximum" cases of icing from the point of view of effect to flight aircraft quality/fitness ratios. In practice can be encountered more dangerous ice formations.

The contemporary turbojet and turboprop aircraft, which possess the greater power reserve in comparison with piston ones to a lesser degree are subjected to the negative effect of icing on such characteristics as rate of climb, service ceiling, cruising and maximum speeds. For example, the aircraft of Tu-104 during tests twice fell under the conditions of especially intense icing, but this did not lead to any serious deteriorations in the flight characteristics. In working de-icing system the rate and the rate of climb of aircraft changed insignificantly. In entire speed range the aircraft handling virtually did not change. However, in the case of the inoperative or insufficient effective de-icing system, as shown in experiments on the aircraft of An-10, Il-18, Tu-124 and An-24, effect of icing it can prove to be very essential.

So, on the aircraft of Il-18 the decrease of cruising speed in flight under conditions of icing with switched off system at the height/altitude of 4000 m was 40 km/h according to instrument. On the aircraft of An-10 deceleration according to instrument was even more noticeable and it was 50-60 km/h at the height/altitude of 3000 m during the stable operation of engine. It is characteristic that in both cases occurred the icing of the first form with the large zone of the propagation of ice along chord, moreover the thicknesses of ice on the aircraft of Il-18 it was altogether only 12 mm, and on the aircraft An-10-20 mm (on standard indicator). Analogous results were obtained, also, on the aircraft of Tu-124 and An-24. On the aircraft of Tu-124 with deposit on wing and tail assembly of uneven semitransparent ice, close to the first form (by thickness on indicator 10-12 mm), indicated airspeed decreased from 350 to 300 km/h. Flight was accomplished at the height/altitude of 2000 m at temperature of surrounding air of -5°C with switched off de-icing system. The width of the capture/grip of ice on wing and tail assembly was within the limits of 100-200 mm.

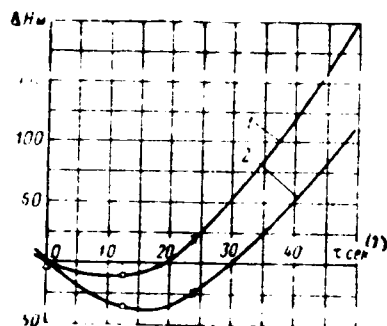


Fig. 4.9. Rate of climb of the iced over aircraft with drift to the second circle (icing of the first form; the thickness of ice on standard indicator 70-75 mm). 1 - moniced aircraft, 2 - iced over aircraft in working de-icing system. Δ - moment/torque of the giving of the gas; \circ - moment/torque of landing gear retracting; \times - moment/torque of retraction of flaps.

Key: (1). s.

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Obvious, however, is the fact that deceleration to 50 km/h for an aircraft of the type of Tu-124 does not have this threatening value as, let us say, for an aircraft Li-2 with its low power reserve and small speed range. Furthermore, one should consider that the de-icing systems of aircraft with gas turbine engines as a whole are

considerably more effective than the systems of piston aircraft.

For the aircraft, equipped by cyclically de-icing system, is of interest the determination of permissible rate of icing in the period, when system is temporarily switched off. Was obtained for several aircraft types series/row the curves, showing in the various forms of icing a change in the rate of level flight in dependence on the thickness of ice on standard indicator.

Curves are constructed according to the data, obtained on aircraft Li-2, Il-12, Il-14, Il-18, An-10, An-24, Tu-124 and are related to the conditions for cruise at the height/altitude of 2000-4000 m during the stable operation of engine with the switched off de-icing system of wing and tail assembly (Fig. 4.10).

The curves I and II are obtained respectively for the first and second forms of icing and are the envelopes, which limit the region of the lines which are related to the icing of intermediate form. Dotted line for an example showed the curves, which relate to the specific cases of the icing of different aircraft.

The given dependences show that a decrease in the velocity occurs most sharply in the initial period of icing. subsequently an increase of the thickness of ice in smaller measure affects rate

change. This can be explained by the fact that the icing already at the very beginning (with the thickness of ice 15-20 mm) qualitatively changes the character of the flow around profile/airfoil, sharply making aerodynamic characteristics worse. Further increase of ice is no longer introduced substantial changes into flow pattern, causing ever slower decrease in the velocity.

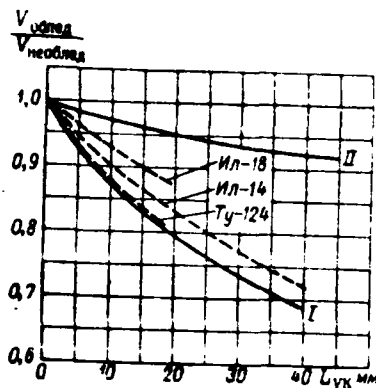


Fig. 4.10. Dependence of the rate of level flight on the thickness of ice $L_{ух}$ on standard indicator in switched off de-icing system. I - icing of the first form, II - icing of the second form.

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Curves characterize rate change with the simultaneous icing completely of wing and tail assembly. The photograph of the iced over wing is given in Fig. 4.11. In the examination of the work of cyclic deicer, of course, it is necessary to consider that the shielded sections of wing and tail assembly will undergo icing not simultaneously. This considerably decreases the effect of icing on rate change.

An increase in the drag of aircraft as a result of icing leads

to a considerable increase in kilometer consumption of fuel/propellant and reduces respectively flying range. For example, for the aircraft of Il-14 reduction/descent as a result of the icing of cruising speed for 30-40 km/h causes an increase in the per-kilometer expenditure/consumption by 15-20o/o. But if we for retaining/preserving/maintaining given speed increase engine power rating, then fuel consumption per kilometer will increase by 40-50o/o.

Special importance has icing to controllability and stability of aircraft.

Fig. 4.12 gives the graph, which characterizes the longitudinal static stability of the aircraft of Il-12 in the case of formation/education on the stabilizer of ice (close to the second form) in thickness approximately 30 mm. With this icing longitudinal static stability noticeably deteriorates, and in the climb at low speeds balancing curve has a region of the static instability. It is characteristic that with the thickness of ice of less than 20 mm the longitudinal static stability changes in comparison with noniced aircraft insignificantly.

Ice accumulation on wing and tail assembly can cause impairment of the control effectiveness. For example, for the aircraft of Il-14

formation/education on the wing or ice in thickness more than 40 mm leads to the fact that the aircraft begins to react to the aileron deflections with considerable delay. Is possible the icing also of very controls (Fig. 4.13).



Fig. 4.11. Ice formation on the wing of the aircraft of Il-14 in switched off de-icing system.

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The effect of icing on aircraft handling is different in different flight conditions. Icing of one and the same form and one and the same of thickness in level flight can not exert the perceptible effect, but in the period of landing approach in flight at low speeds it is essential to lower the control effectiveness.

Let us examine in somewhat more detail the effect of the icing of the tail assembly on the behavior of contemporary aircraft in prelanding mode/conditions, i.e., in this stage of the flight, when a deterioration in the stability characteristics and controllability is

especially dangerous.

The ice built-up edge, which is formed on the leading edge of an airfoil profile of stabilizer, can significantly decrease the critical angle of attack of horizontal tail assembly. The decrease will be different depending on form and thickness of ice built-up edge. Because of this it is necessary to have data on reserve with respect to the critical angle of attack of horizontal tail assembly in the mode/conditions of landing approach in the case of possible ice formation in the case of the failure of de-icing system or its ineffective work.

As is known, the wing of aircraft, reflecting air down, changes its direction in the field of horizontal tail assembly, creates the so-called downwash whose value directly depends on the lift coefficient of wing. Is the more C_L wing, the greater the downwash angle. Downwash in horizontal strut tail assembly is various for different airplane configurations: the above arranged/located horizontal tail assembly, the less the downwash angle, which flows around about the stabilizer.

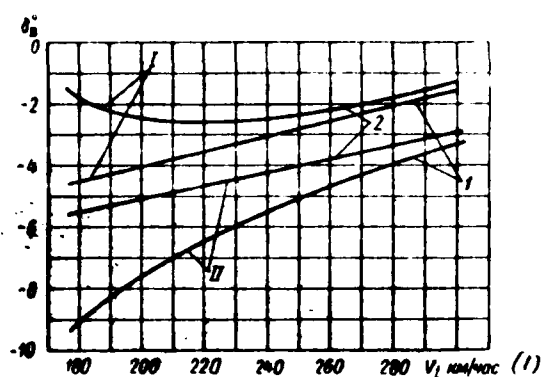


Fig. 4.12. Balancing curves of the noniced (1) and iced over (2) aircraft in the case of formation/education on the stabilizer of ice in thickness approximately 30 mm. I - climb; II - reduction/descent.

Key: (1). km/h.

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The special feature/peculiarity of contemporary aircraft is the powerful/thick high-lift device or wing, consequence by which is a considerable additional increase in the wing downwash. In Fig. 4.14 it is schematically shown that the downwash leads to increase of true angle of attack horizontal tail assembly it works on negative ones angles of attack.

On aircraft with turboprop engines supplementary adverse effect from this point of view can exert the use of the increased installed power, which leads, as a result of the amplification of the airflow of screws/propellers, to an increase in the wing downwash and, therefore, to further increase in the negative angle of attack of horizontal tail assembly.

With the work of horizontal tail assembly on the angles of attack, close to critical, can arise sufficiently serious changes in the stability characteristics and aircraft handling, first of all - in stability with respect to y -force.

It is logical that the phenomena indicated can be observed only with the insufficient effectiveness of de-icing system (or in the case of its failure), when ice formation on the leading edge of stabilizer leads to the decrease of the critical angle of attack of horizontal tail assembly.

The study of the effect of icing on the characteristics of longitudinal stability and controllability was carried out on three types of specially equipped turbojet aircraft [19]. Flights were fulfilled under conditions logically of icing.

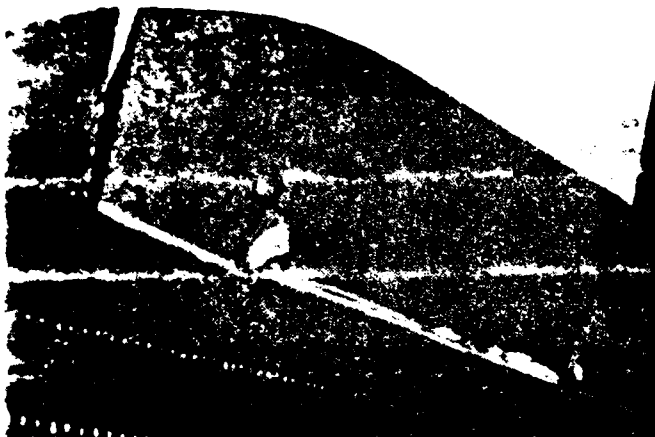


Fig. 4.13. Icing of aileron.

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On stabilizer they increased ice of various forms and thickness in switchel off de-icing system. After ice formation of intended size the aircraft left cloudiness and at safe height/altitude were determined the characteristics indicated.

For obtaining the balancing curves of straight flight were fulfilled the dispersals/accelerations and brakings with extended gears and deflected flaps, corresponding to their position during

landing. it howled established/installed, that the longitudinal-behavior characteristics by the rate with the icing of stabilizer in the majority of the cases quantitatively differ little from analogous characteristics in the absence of icing. However, in certain cases was fixed the appearance of the buffeting of horizontal tail assembly in the mode/conditions of dispersal/acceleration with the deflected flaps.

For obtaining the balancing curved deflections of the elevator and efforts/forces on handwheel in dependence on g-force were carried out the deflections ("giving") of elevator "from themselves" in extended gear and landing position of flaps in the range of the velocities, corresponding to landing approach. an example of this deflection of elevator is shown in Fig. 4.15, where is given change in the time of some parameters of the axial motion of aircraft, which characterize its stability and controllability. As is known, pilot perceives the aircraft control by means of the efforts/forces, which appear on control levers with the execution of one or the other maneuver. The important criterion of controllability and stability is value dP_h/dn_y , which characterizes the value of the effort/force on handwheel, required for changing the g-force per unit.

The dependence of required efforts/forces on handwheel on g-force usually bears almost linear character (to a definite limit).

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For the creation of large in magnitude g-force are required large efforts/forces on handwear.

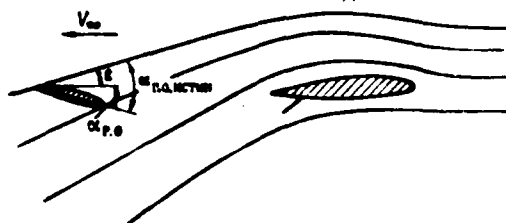


Fig. 4.14. Effect of wing downwash on an increase in the true angle of attack of horizontal tail assembly.

$\alpha_{D.O.}$ downwash angle, $\alpha_{T.O. + D.O.}$ the true angle of attack of horizontal tail assembly, $\alpha_{T.O.}$ the angle of attack of horizontal tail assembly in the absence of downwash, V_∞ direction of the undisturbed flow.

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Experiments showed that with ice formation on stabilizer possibly sharply a change in the efforts/forces on handwheel in comparison with the noniced aircraft. At the specific sizes of the g-force derivative dP_y/dn_y becomes equal to zero and even acquires negative sign.

Fig. 4.16 and 4.17 give as an example the results of determining longitudinal-behavior characteristics with the icing of stabilizer

for two types of turboprop aircraft ¹ (with four engines).

FOOTNOTE ¹. Experiments are carried out by the author together with engineers A. A. Bondarenko and A. B. Ivanov. ENDFOOTNOTE.

As can be seen from Fig. 4.16, with formation/education on the nose/leading edge of the stabilizer of tapered ice built-up edge (in thickness approximately 8 mm and width of 20-25 mm) required efforts/forces on handwheel are considerably decreased. When $n_y=0.65$ derivative $dP_B/dn_y=0$, while with further decrease of g-force is a tendency toward the disappearance of efforts/forces on handwheel.

The decrease of efforts/forces on handwheel with icing depends on a change in the hinge moments as a result of redistribution of pressure on horizontal tail assembly, which, in turn, is caused by the appearance of local flow separations on the lower surface of stabilizer. With accomplishing of experiment on this aircraft on leaving g-forces less than 0.7, appeared the considerable buffeting of horizontal tail assembly, which also testified about approximation/approach u_{cr} to critical value. With the icing of stabilizer characteristic is the fact that even ice of small thickness represents danger. Under conditions of intense icing ice built-up edge in 8 mm can be formed during 3-4 min. This is shown, how inadmissibly any a delay of the start of de-icing system.

Fig. 4.17 gives analogous graph for another aircraft type. the thickness of ice on stabilizer was 20-25 mm, the width of 60-70 mm. in contrast to the preceding/previous graph where the curve of efforts/forces with the ice on stabilizer is smoothly deflected off by the curve of the noniced aircraft, we see that ice formation of the sizes/dimensions indicated and form led to a sharp qualitative change in the longitudinal-behavior characteristics with respect to g-force. Curve "with ice" coincides with curve "without ice" up to g-force 0.5. However, with g-forces less than 0.5, efforts/forces on handwheel sharply are reduced, and when $\alpha = -0.2$ they reach zero. This character of the sudden and sharp decrease of efforts/forces on handwheel with landing approach is the very undesirable phenomenon and indicates that the conditions for the flow around horizontal tail assembly with approximation/approach to critical angle of attack change in this case considerably more rapidly and it is sharper than in preceding/previous.

As it was noted above, downwash in the region of horizontal tail assembly is directly connected with the flap angle.

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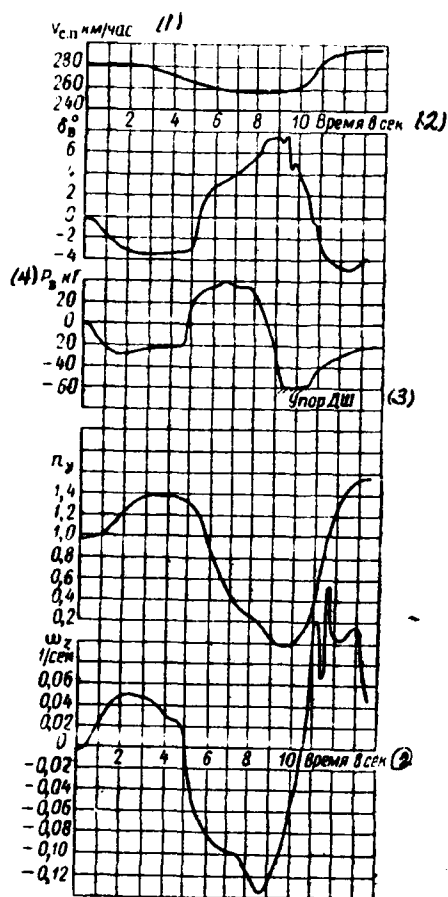


Fig. 4.15.

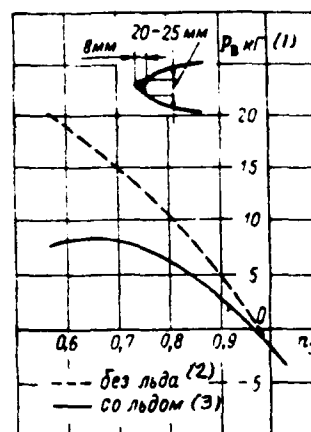


Fig. 4.16.

Fig. 4.15. Change in time of speed $V_{сн}$, elevator angle δ , of effort/force on handwheel P , of vertical g-force n_y , and angular velocity ω_z , upon elevator input under the conditions of pre-landing glide with icing of stabilizer of aircraft.

Key: (1). km/h. (2). Time in s. (3). Backstop. (4). kgf.

Fig. 4.16. Change in longitudinal stability with respect to g-force for turboprop four-engine aircraft during deposit on stabilizer of ice with a thickness of 8 mm. The flap deflection corresponds to their position in landing. Flight speed and engine power rating correspond to landing approach.

Key: (1). kgf. (2). without ice. (3). with ice.

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Fig. 4.18 depicts a change in longitudinal stability in g-force for an aircraft with two turboprop engines with the icing of stabilizer at different flap angles of 15°, 30° and 40°.

Most sharply the effect of icing is developed with the flaps, deflected on 40°. In this case upon reaching the g-forces of 0.55 efforts/forces on handwheel disappear, and with further decrease of g-force they acquire negative value. With the flaps, deflected on 30°, the icing of stabilizer exerts smaller, but nevertheless serious effect on the longitudinal stability of aircraft. And only with the

flaps, deflected on 15° , the dependence of required efforts/forces on handwheel on g-force carries almost linear character, up to the sizes of the g-force 0.3-0.4 effect of icing virtually is not perceived. This however does not mean that with larger than 15 mm to the thickness of the ice built-up edge of stability characteristic cannot considerably deteriorate, also, with the flaps, deflected on 15° .

Characteristic for this aircraft type was the fact that ice of tapered form exerted smaller influence on longitudinal-behavior characteristics.

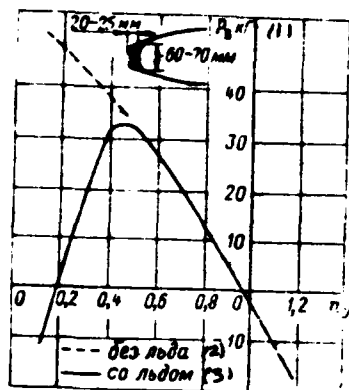


Fig. 4.17.

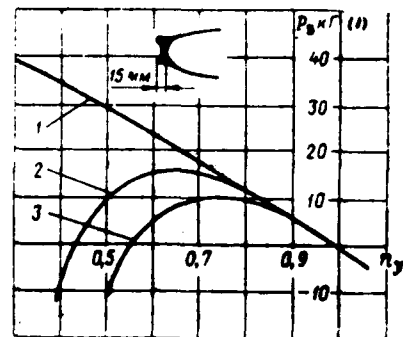


Fig. 4.18.

Fig. 4.17. Change in longitudinal stability with respect to g-force for aircraft with four turbojet engines with icing of stabilizer. (Flap deflection corresponds to their position in landing. Flight speed and engine power rating correspond to landing approach).

Key: (1). kgf. (2). without ice. (3). with ice.

Fig. 4.18. Change in longitudinal stability with respect to g-force for aircraft with two turboprop engines with icing of stabilizer (flight speed and engine power rating correspond to landing approach). 1 - flaps are deflected on 15°, 2 - flaps are deflected to 30°, 3 - flaps are deflected on 40°.

Key: (1) - kgf.

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Longitudinal-behavior characteristics were determined also with the formation of "barrier" ice on stabilizer. In particular with the thickness of "barrier" ice after warmed by zone n of the upper surface of nose/leading edge of approximately 7 mm¹ (see Fig. 3.39) were obtained longitudinal-behavior characteristics in the mode/conditions of landing approach, which proved to be satisfactory with certain tendency toward the decrease of longitudinal stability level with respect to g-force on low ones C_y .

FOOTNOTE 1. On the lower surface of the nose/leading edge of stabilizer the thickness of barrier ice was somewhat less.

ENDFOOTNOTE.

Apparently, ice accumulation on the boundary of the warmed zone of the nose/leading edge of stabilizer in principle has smaller effect than the formation/education of ice buildup directly on leading edge. However, one should expect that the formation of ice deposits on the lower surface of stabilizer at a great distance from nose/leading

edge can prove to be dangerous. This formation/education is possible with strong the spreading or the settling water.

The given materials it shows that with an increase in the negative angle of attack of horizontal tail assembly the ice built-up edge, which was being formed on the leading edge of stabilizer, can lead to an abrupt change in the character of the flow around stabilizer in comparison with noniced.

Although under the normal conditions for operation the output of aircraft on overload, considerably smaller unity, is very little probable however there are some following supplementary factors, which can contribute to the approximation/approach of the angle of attack of horizontal tail assembly to critical. Above has already been mentioned about this adverse moment/torque as increased engine power rating. The significant role can also play an increase in the velocity with landing approach over that recommended. With an increase in the velocity of flight of aircraft is decreased the angle of attack of wing, which leads to an increase in the negative angle of attack of horizontal tail assembly. Adverse from this point of view is the light gross weight of aircraft. Thus, to pilot it is necessary to consider that all factors which in prelanding flight conditions one way or another can lead to an increase in the negative angle of attack of horizontal tail assembly, play negative role. They

include: the extension of flaps on the large angle, the increase in engine power rating (especially average/mean for an aircraft with four engines), an increase in the velocity with landing approach, light gross weight, turbulence and sharp piloting, which can lead to the creation of considerable g-forces.

It is necessary to again emphasize that all given graphs are related to the case of switched off de-icing system and, therefore, under actual conditions can be examined as failure the systems or its overdue start. Upon the overdue inclusion of system under conditions of icing occur the individual cases of decreasing the efforts/forces on handwheel and the "pecks" of aircraft in prelanding mode/conditions.

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Pilot must remember that in with reduction/descent one must break clouds under conditions of possible icing, de-icing system should be included in advance. After the inclusion of system it is necessary to be convinced of its normal operation.

Landing approach under conditions of icing with the refused de-icing system of the tail assembly one should execute with the incomplete flap deflection or, if are allowed the sizes/dimensions of

airfield, with the retracted flaps. in this case the pilot must not allow/assume the sharp piloting and the onset of considerable negative g-forces.

Another question for piston and turboprop aircraft is the effect of the icing of propeller blades. In each specific case it is necessary to establish/install, to what extent can ice formation of one or the other thickness on blades/vanes impair the propeller efficiency. For the illustration of this effect is given the graph in Fig. 4.19, where is shown a change in the vertical velocities of aircraft in one and the same conditions of icing. The determination of rate of climb was produced by ice formation, close to second form, by thickness on standard indicator 40 mm.

As can be seen from graph, the rate of climb of aircraft descends with the icing of blades/vanes very considerably.

It should be noted that for different aircraft types and propellers the effect of the icing of blades/vanes on the propeller efficiency can be different: for some aircraft the decrease of efficiency can reach the value of order 150/o and more, but for others - it is incomparably less. For example, for the aircraft of Il-12 was revealed that device for protection from the icing of propellers virtually it is not required.

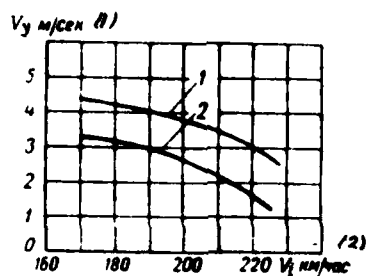


Fig. 4.19. The vertical velocities of the iced over aircraft with noniced blades/vanes (curve 1) or propeller and with the iced over blades/vanes (curve 2) (icing, close to the second form. Thickness of ice on standard indicator 40 mm).

Key: (1). m/s. (2). km/h.

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Chapter V.

INFORMATION ABOUT THE TESTS OF AIRCRAFT AND HELICOPTERS UNDER
CONDITIONS OF ICING.

After development and creation of de-icing system arises the question, by what methods and under what conditions must be established/installed the suitability of this system and this aircraft (helicopter) to operation under conditions of icing.

For all flight vehicles, permitted to IFR flights, must be established/installed: a) how effectively operates the de-icing system; b) the how possible effect of icing on the flight of aircraft (helicopter) in the case of the failure of system.

In the first case it is necessary to determine, is provided jettisoning ice or prevention of its formation/education under the design conditions of icing, does allow/assume de-icing system any ice accumulations, are such its possible maximum formation/educations under most adverse conditions and what this can influence behavior of aircraft. In this case sometimes arises the question about the effect

of "barrier" ice, which is formed beyond the limits of heating surface, or "cyclic" ice, i.e., ice which in cyclic systems periodically appears in one or the other section of the shielded surface with the temporary/time disconnection of the heating of this section.

In the second case it is necessary to establish what happens with aircraft under conditions of icing in different flight conditions in the case of the failure of de-icing system and what in this case recommendations must be given to pilot. For a contemporary aircraft, in the first place, attention must be turned to the effect of icing on the characteristics of stability and controllability and to the operation of power plants.

There are several methods of solving the presented questions.

The determination of the effectiveness of de-icing system can be performed by measuring the thermal characteristics of system (temperature drops) during flights in "dry" air (out of clouds), by tests in the artificially created icing and finally by conducting the flights under conditions of natural icing.

It is obvious that if the first method gave the confident solution of task, would be eliminated need in two others. However, as is shown experiment, up to now the method of temperature drops did not give the completely reliable evaluation of de-icing system and was only the preliminary stage, necessary, but insufficient.

It should be noted that the method of temperature drops, naturally, let us use only for thermal systems. The measurement of temperature drops on heating surface of wing, tail assembly and other parts is produced in the majority of the cases with the aid of thermocouples or flat/plane resistance thermometers, stuck on skin/sheathing. The method of the patch of thermometers plays the significant role in the precision/accuracy of measurements. The recording of temperatures is produced by the chart recorders, providing the possibility of the simultaneous recording of a large number of parameters (quantity of points, at which is measured the temperature, it usually reaches hundred).

Tests of de-icing systems on the flying laboratories which imitate icing by pulverizing water, has the series/row of the advantages, most important of which are the possibility of preliminary test of the elements of new de-icing system even to the termination of the construction of the first experiment aircraft, and also the possibility of designing of the conditions icing, which

correspond to calculations. The latter is especially important. This method widely is applied in England, USA, Canada and other countries. Its shortcoming is the fact that at the imitation of icing it is not reached complete agreement of the obtained forms and forms of ice to those which are encountered in actual conditions. Furthermore, method does not make it possible to check de-icing system as a whole in that form, in which it must be established/installed on production aircraft. However, taking into account the positive aspects of this method, it is necessary to recommend its wider use/application.

Fig. 5.1 shows the appearance of the laboratory aircraft on which is established/installed the engine, which passes tests under conditions of artificial icing. Before the engine are installed injectors for the atomization of water. In Fig. 5.2, borrowed from work [31], is shown the icing of power plant, obtained artificially, at water content of clouds 1.9 g/m^3 and temperature of surrounding air of -20°C . Sometimes tests in artificial icing are conducted not on the special flying laboratories, but by the setting up of the system of the atomization of water directly on the experience/tested aircraft as that it is shown in Fig. 5.3, undertaken from the same work.

At international conference in 1962 on the problem of fading it was communicated [52] about interesting experiments of the imitation of the conditions of icing with the aid of the special aircraft-tanker, in tail section of which is arranged/located the spattering device/equipment (Fig. 5.4). This aircraft-tanker, completing flight in front of the experience/tested aircraft, via atomization creates the cloud of the supercooled drops of the prescribed/assigned concentration and sizes/dimensions. The greatest difficulty during the use/application of this method is the need for strict maintaining of the distance between two aircraft and the complexity of accomplishing the paired flight.

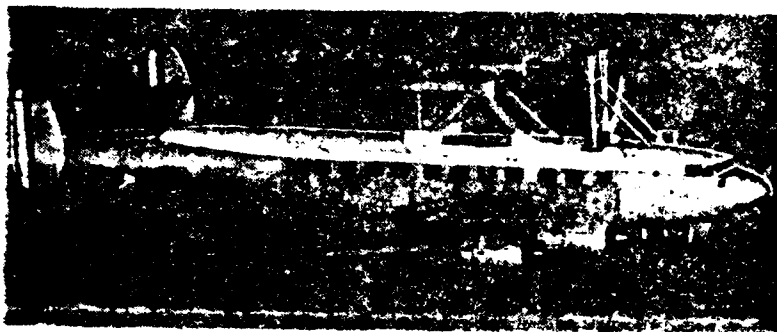


Fig. 5.1. Flying testing laboratory of de-icing systems under conditions of artificial icing.

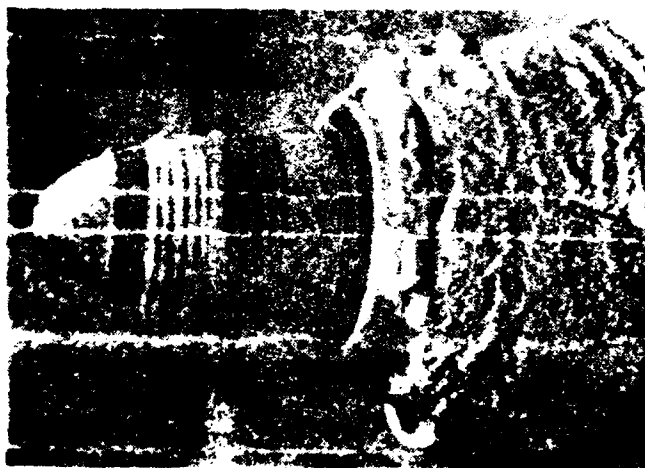


Fig. 5.2. testing power plant under conditions of artificial icing.

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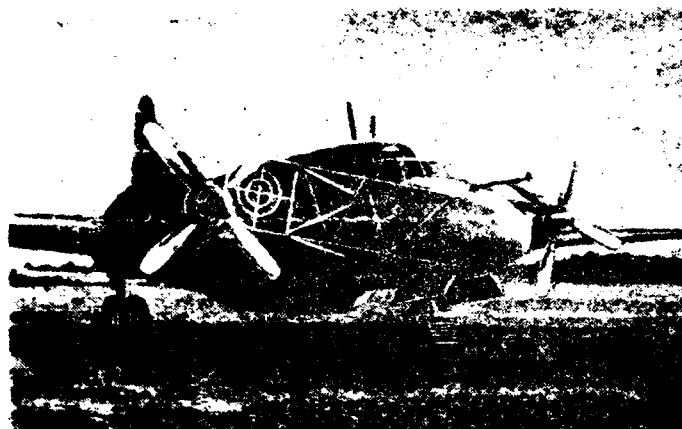


Fig. 5.3. Setting up of system of atomization on experience/tested aircraft.

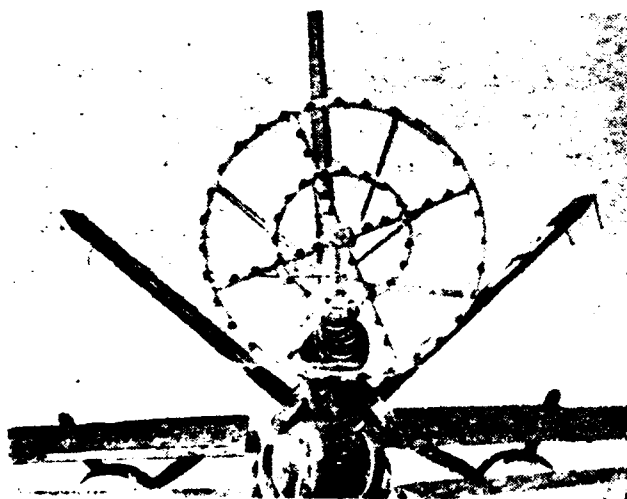


Fig. 5.4. Device for atomizing water, installed in the tail part of an aircraft-tanker.

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This method can be used also for the imitation of rain and crystal icing.

Especially high value has the imitation of icing for the helicopters whose tests in natural icing are connected with risk and great difficulties. In Fig. 5.5 is given the photograph, which illustrates the flight of helicopter artificially created cloud.

For the tests of the instruments of certain equipment and small-size sections of deicers, frequently are applied wind tunnels. Diagram of one of such tubes is shown in Fig. 5.6 [44].

Tests in natural icing as any checking under actual conditions, are the best and most reliable method of determining the effectiveness of the deicers of aircraft. However, this method is connected with the considerable difficulties, caused by the search of such conditions of the icing with which must be tested the de-icing system. As is shown experiment, for obtaining the sufficiently reliable evaluation of the effectiveness of de-icing system during tests under conditions of natural icing is required flight time in space from 30 to 60 hour.

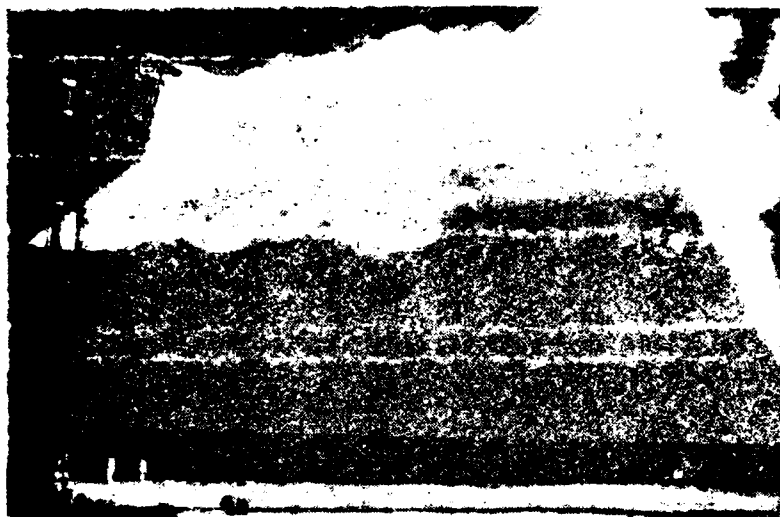


Fig. 5.5. Installation for testing the helicopters under conditions of artificial icing.

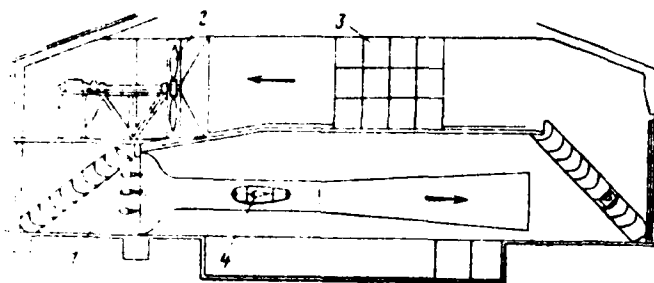
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The statistical material, given in Fig. 2.7 and 2.8, makes it possible to propose Table 16.

Data given in table are close to 90-95o/o quantiles of relative icing intensity. Despite the fact that these data are understated in comparison with those conditions of the icing to which must be designed the de-icing system, experiment shows that the 15-minute

flight under conditions, which correspond to table, makes it possible to sufficiently reliably rate/estimate the effectiveness of deicing equipment.

The conditions of natural icing, given in table, are more are clearly demonstrated on graph (Fig. 5.7), where for an example is plotted/applied also the curve of the velocity of the increase of ice on standard indicator in mm/min at true airspeed of aircraft 500 km/h.



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Fig. 5.6. Wind tunnel for tests under conditions of artificial icing.
1 - injecting injectors, 2 - fan, 3 - cooling device, 4 - test specimen.

Table 16. The standard conditions of natural icing for the tests of deicing system ¹.

FOOTNOTE ¹. Analogous table was recommended by the author earlier in work [18]; however, the data given in it, as showed later analysis, required certain refinement. ENDFOOTNOTE.

(1) Температура наружно- го воздуха °C	(2) Относительная интен- сивность обледенения указателя в мм/км	(3) Время непрерывного нахождения самолета в условиях обледенения мин
-5	0,7 и более	(5) не менее 15 мин
-10	0,4 и более	"
-15	0,25 и более	"
-20	0,15 и более	"

Key: (1). Temperature of surrounding air of °C. (2). Relative icing intensity of indicator in mm/km. (3). Time of continuous determination of aircraft under conditions of icing min. (4). and more. (5). it is not less than 15 min.

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Curve shows, for example, that for the evaluation of de-icing system at temperature of -15° , the icing intensity must be not less than 2 mm/min.

It is necessary to remember that the tests of de-icing system under conditions of natural icing must be carried out with the formation/education of two fundamental forms of ice. This is connected with the fact that for the operation of system it is not unimportant, will be ice formed in the narrow or wide section of the leading edge of an airfoil profile. This requirement always in proper measure is not considered. While conducting of tests under conditions of natural icing considerable difficulty presents the precise measurement of the temperature of surrounding air, since the usual temperature-sensing devices are covered/coated with ice and give error in their readings. During flights under conditions of icing it is necessary for measuring the temperature of surrounding air to apply the special shielded thermometers.

Response/answer to the second aspect of the task of the determination of the suitability of aircraft to flights in the zones

of icing (in the case of the failure of de-icing system) also can be obtained by several methods: wind tunnel test, flight tests with the mock-ups of the various forms of ice and by natural condition test of icing. The first two methods must find use predominantly on the early stages of creation and introduction of the aircraft; to them must be allotted considerably larger attention, than this now occurs. Checking under conditions of the natural icing of the effect of two fundamental forms of ice on aircraft performance, on the operation of engines is the necessary final stage. Such tests are rather complicated and require large experiment and qualification of experimenters; however, they are completely possible, as this shows practice.

The procedure of the flight performance test of aircraft with the icing of its parts (both in working de-icing system and with the imitation of its failure) is reduced to following. Aircraft completes flight in the zone of icing until on its surface is formed ice of the prescribed/assigned form and sizes/dimensions. If is placed the task of determining the effect of icing by the failure of de-icing system, then flight is accomplished with shut-off deicers.

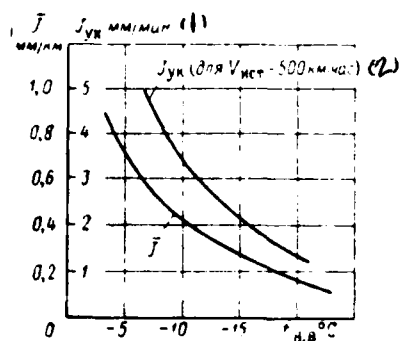


Fig. 5.7. The standard conditions of natural icing during the tests of de-icing system.

Key: (1). mm/min. (2). km/h.

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If it is necessary to rate/estimate the effect of ice, which appears with the operation of system, flight is accomplished with working deicers, in this case the conditions of icing (its intensity, duration, temperature of surrounding air) must correspond to standard ones. After the "set/dialing" of ice the aircraft leaves the zone of icing (as a rule, upward) and at safe height/altitude with the specific excess above the upper cloud boundary are made the necessary maneuvers for obtaining one or the other characteristics. The

difficulties of experiment consist in the searches of the necessary conditions, in the complexity of retaining/preserving/maintaining the initial form and the sizes/dimensions of obtained ice, and also frequently in the impossibility of the repetition of experiment under identical conditions.

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Chapter VI.

GROUND-BASED ICING.

The aircraft icing and helicopters during their layover on the earth/ground has its special features/peculiarities.

This problem also plays large role in providing of flight safety; however, since all instructions and management/manuals forbid taking off of iced over aircraft, ground-based icing, in the first place, affects the regularity of air traffic. From practice are known the cases, when ground-based icing in the absence of the effective combat means with this phenomenon delayed for a prolonged time the flights of many aircraft, after doing large damage.

The numerous and diverse forms of ground-based icing can be combined into three basic groups [20].

The first group includes those, that are formed as a result of transition/transfer (sublimation) of vapor into ice, passing liquid phase. Here enter hoarfrost, solid (crystal) raid and crystalline

frost. Hoarfrost appears in clear calm weather on the surface of the objects/subjects, cooled by the radiation/emission of heat and having lower, than air, minus temperature. Near the surface of object the air is cooled, and the water vapor containing in it, after achieving saturation state, is converted into ice.

Hoarfrost can be formed with any negative temperature and with most varied relative air humidity.

Solid (crystal) deposit appears with potentials when the objects retain lower negative temperature than the attached warm air masses of air. The thickness of hard rime does not usually exceed several millimeters.

The crystalline frost is formed in severe frost as a result of the supersaturation of air by water vapor.

All three means of snow-visible deposits are fragile, they have low density and they can be comparatively easily distant from the surface of aircraft.

To the second group can be attributed the forms of icing. connected with the presence in the atmosphere of supercooled water. In this case ice is formed as a result of crystallization on the

surface of the aircraft of the supercooled drops of rain, fog or drizzle.

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On structure, appearance, color the icing can be different: from transparent glassy ice to snow- white deposit, similar to hoarfrost. Difference is caused by the fact that under varied conditions the velocity of the freezing of drops is different. If temperature oscillates in limits of 0--5°C (are known the cases of forming the ice-covered surface, also, at temperatures of -10--14°C), then major drops, freezing, spread over body surface and is formed transparent glassy ice (sleet). At low temperatures small/fine drops freeze rapidly and it is formed mat or white ice. The smallest drops of the supercooled fog, freezing, form the granular frost.

The ice deposits of the second group considerably more durably are engaged with the surface of aircraft than sublimation, and they can reach large sizes.

To the third group can be attributed all forms of ground-based icing, which are formed as a result of freezing on the surface of the aircraft of the usual nonsupercooled water (rain, wet snow, deposited drops of fog, the condensate of water vapors, etc.). In appearance

they are similar to the deposits, in reference to the first two groups, but in contrast to sublimation ice solidly they are linked with the surface of aircraft.

Frequently any snow-visible ice accumulation on the surface of object/subject erroneously is called it has. This can lead to the incorrect evaluation of adhesion strength of ice with the surface of aircraft. Never one should rely on the fact that any form of ground-based icing there will be destroyed as a result of the buffeting of aircraft with taxiing or under the action of air flow.

The wing profile of the aircraft iced over on the ground changes differently from with icing in air. If in flight ice is formed only on the frontal aircraft components, turned to the incident flow, then on the earth/ground it covers/coats the large part of the surface of aircraft - usually entire upper part of the wing and tail assembly, and also surface of fuselage (Fig. 6.1).

The special feature/peculiarity of ground-based icing is its dissymmetry. Frequently the wind direction does not coincide with the longitudinal axis of aircraft. In this case icing undergoes that side of aircraft which is turned to wind.

With takeoff on the iced over aircraft main danger consists in

the onset of premature and sharp flow separation from wing. Aircraft during takeoff in the beginning of the climb is piloted at high angles of attack, flight on which on the iced over aircraft represents the greatest danger.

As is known, with takeoff the noniced aircraft completes run until achievement of unstick speed V_{orp} , when

$$Y = G = c_{y\,orp} \frac{\rho S V_{orp}^2}{2},$$

where Y - the lift;

G - weight of aircraft.

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Usually coefficient $c_{y\,orp}$ is less $c_{y\,max}$ to 15-20%.

If on any reasons upon reaching V_{orp} coefficient c_y does not achieve value $c_{y\,orp}$ and lift will be lesser than the weight of aircraft, then for its increase (as this follows from formula) can be used two paths: further increase in the velocity due to an increase in the takeoff run length or increase in coefficient c_y by transition/transfer to larger angle of attack. But for a takeoff/run-up the length of airfield can prove to be insufficient, and an increase in the angle of attack to its critical value can lead to flow separation from wing.



Fig. 6.1. Ground-based icing of the tail assembly (a) and the fuselage (b) of aircraft Li-2.

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Since coefficient, lifts of the iced over wing are less than in

noniced, then pilot, completing takeoff at the angle of attack of wing α_{0TP} and seeing that the aircraft upon reaching of usual (for noniced) unstick speed does not take off, it can accelerate the takeoff of aircraft, after taking handwheel for itself, after increasing to these angle of attack. In this case necessary value C_y can be achieved/reached, but already at such angle of attack, which is for the iced over aircraft critical. This can lead to the fact that if the aircraft is detached away from the earth/ground, then with a most insignificant further increase in the angle of attack will occur overall flow separation from wing and decrease C_y .

But if, after achieving V_{0TP} for noniced aircraft pilot it will not increase angle of attack, and aircraft it will continue run to the large velocity (under the condition, of course, that the boundaries of airfield make it possible this to make), then aircraft can be detached away from the earth/ground. However, this yet does not mean that the subsequent stages of takeoff will be travelled by the iced over aircraft happily.

An increase in the takeoff run length of the iced over aircraft is caused mainly by an increase in the drag: the increase of runaway speed will occur slowly. Usual V_{0TP} for noniced aircraft will be achieved/reached after the larger time at larger takeoff run length. Since in this case the aircraft must continue takeoff/run-up for

achievement of the velocity, which exceeds V_{crp} for noniced aircraft, takeoff run length will increase still more. After the breakaway of aircraft from the earth/ground for it one must still overcome obstructions in approach area. Due to the impaired rate of climb the trajectory of climb on the iced over aircraft will be flat, and this will force pilot to increase angle of attack, which again can lead to the dangerous disruption/separation of air flow from wing. It is necessary to stress that the premature disruption/separation of air flow can be, also, after the termination of takeoff. For example, with turns in the climb at low speed, with a change in engine power rating (piston and turboprop), when with the partial retraction of gas is decreased the supplementary airflow of wing by air flow from screws/propellers, which decreases lift. With accomplishing by the aircraft of turn (without reduction/descent) the lift, as is known, must be increased. this can be achieved/reached either by an increase in the velocity or by an increase in the angle of attack. in the latter case appears anew the danger of approximation/approach to the critical angle of attack which is considerably reduced in the iced over aircraft. Furthermore, bank with turn leads to a local increase in the angle of attack in the listing wing and to the possibility of the appearance of very dangerous one-way disruption/separation of air flow.

Besides the danger of the disruption/separation of air flow, serious value has also reduction/descent in the effectiveness of all controls in the iced over aircraft. In particular, the icing of wing in those sections where are arranged/located ailerons, and also icing of ailerons themselves can cause sharp worsening of transverse controllability of aircraft.

In chapter IV was examined that a deterioration in the flight characteristics of the aircraft can occur with the very small thicknesses of ice. Difficulties with takeoff can arise with the most insignificant icing of the wing surface. Ice accumulation on the surface of aircraft in large quantities, for example wet snow, can so distort the form of the wing profile and tail assembly and impair aerodynamic characteristics, that breakaway of aircraft from the earth/ground will generally become impossible. Supplementary factor here can prove to be the weight of the forming ice. For example, if ice with a thickness of 5 mm covers surface with area of 100 m², then its weight can reach 400-450 kg.

From that examined it is clear, what danger is takeoff on the iced over aircraft and why it must be forbidden even during the very, it would seem, insignificant deposit of any of the forms of icing on

the surface of aircraft.

Is necessary careful cleaning ice, hoarfrost or snow from aircraft, especially wing and tail assembly, moreover observation of surface condition of aircraft must be conducted up to taxiing to executive start. In practice occurred the cases when the purified surface of aircraft within short time (10-20 min) was covered/coated with the layer of wet snow which with an insignificant change in temperature (upon transfer from small positive temperature to negative) was converted into the incrustation of ice. It can happen, that the aircraft, thoroughly purified from wet snow, during the period of short-term layover in station and taxiing to start will be covered with the incrustation of ice, but crew, without having checked again surface condition of aircraft, will attempt to complete takeoff. It is especially important to follow surface condition of aircraft with takeoff under nighttime conditions.

Deicing of aircraft on the earth/ground can be conducted by both the via their preservation from icing and by distance from the surface of the aircraft of already formed ice.

The difficulty of developing the effective methods is connected with the great variety of the forms of ground-based icing.

It is obvious that hangar storage of aircraft would make it possible to solve problem. However, this method is too expensive and barely suitable for that large quantity of civil/civilian and military aircraft, which at present are operated.

To protect aircraft from icing on the earth/ground is possible via covering. This method is effective under use condition for the covers of the material, which corresponds to definite requirements (watertightness, ease/lightness, strength, air permeability, frost-resistance, etc.).

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A shortcoming in the method consists in labor expense and complexity of the very process of covering, especially for large aircraft, and also in the possibility of the icing of covers themselves. In connection with the fact that up to now is not developed the material for covers, which completely corresponds to requirements, the use/application of this method in practice makes it possible to only partially shield aircraft from ground-based icing.

The large number of works and investigations, which were being carried out on the search of the methods of the preservation of aircraft from icing, was devoted to the physicochemical methods whose

essence consists in the creation of special coatings, which decrease the cohesive force of ice with the surface of aircraft. However, as showed experiment, all proposed coatings proved to be insufficiently effective, since the cohesive force of ice, in spite of its decrease, it remained still considerable. For example, the adhesion power of ice to this hydrophobe as polystyrene, is 2.2 kgf/cm^2 [4], which requires for the removal of ice of some supplementary means.

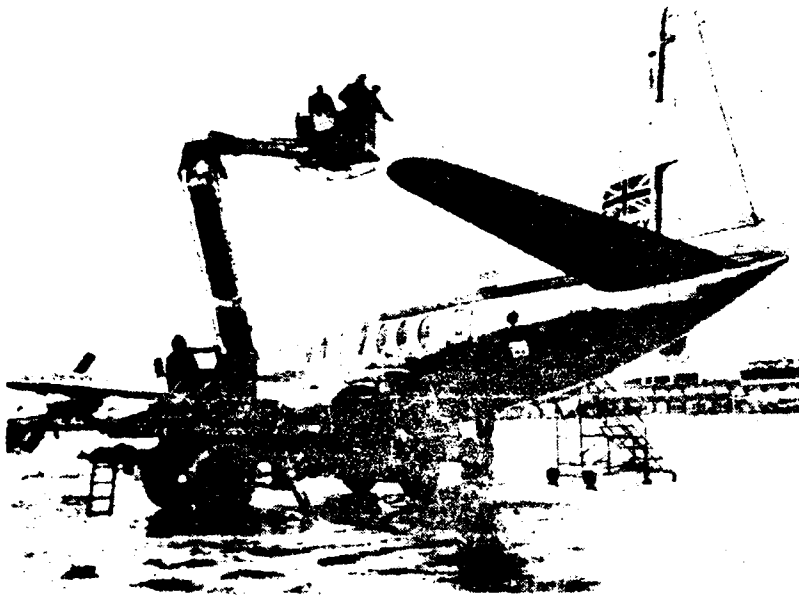


Fig. 6.2. Installation for removing ice from the tail assembly of aircraft "Viscount" with the aid of the heated mixture of water and liquid DS-2a.

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Sufficiently wide application in operation found at present the method, based on the removal of ice formed on the surface of aircraft of the water and of the liquid heated by mixture, reducing the freezing point of water. As is known, the distance of ice by hot water very effective method; however, its fundamental shortcoming is,

the fact that at temperatures of air of lower than -5°C (and especially in the presence of wind) water on the surface of aircraft rapidly freezes, and aircraft anew proves to be the covered layer of ice. In this case is possible the incidence/impingement of water and its freezing in the units of the suspension of rudders, ailerons and i.e. for eliminating this shortcoming it is necessary that after the distance of ice moisture on the surface of aircraft would remain in the liquid state prolonged time until aircraft takes off into air. This is achieved by the use/application of aqueous solutions of the liquids, which have low freezing point (ethyl, isopropyl alcohol, ethylene glycol, glycerin). the aqueous solution of this liquid, heated to $50-60^{\circ}\text{C}$, provides the distance of ice and it prevents the subsequent freezing of water on the surface of aircraft.

Fig. 164 shows the use/application of this method on English aircraft "Viscount". Ice is removed by heated mixture of water and liquid DS-2a whose percentage content is determined by temperature of surrounding air (usually are applied 50o/o solution/opening). Analogous method is applied also on the Soviet aircraft where as liquid with the low freezing point are applied alcohols or ethylene glycol.

Another method to which recently began to be given considerable attention, this distance of ice with the aid of the warm air,

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supplied under pressure. This method combines mechanical and thermal effect, and it is, as show experiments, very promising.

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APPENDIX.

Table of conversion of some values, which are encountered in this book, to SI units.

(1) Наименование величин	(2) Коэффициент для приведения к единицам СИ
Плотность (3)	$1 \text{ г/см}^3 = 1 \cdot 10^3 \text{ кг/м}^3 \quad (4)$ $1 \text{ кг/сек} \cdot \text{м}^4 = 9,80665 \text{ кг/м}^3 \quad (5)$
Давление (6)	$1 \text{ бар} = 10^5 \text{ Н/м}^2 \quad (7)$ $1 \text{ ат} = 9,80665 \cdot 10^4 \text{ Н/м}^2 \quad (8)$
Динамическая вязкость (9)	$1 \text{ кгс} \cdot \text{сек} / \text{м}^2 = 9,80665 \text{ Н} \cdot \text{сек} / \text{м}^2 \quad (10)$
Кинематическая вязкость (11)	$1 \text{ см}^2 = 1 \cdot 10^{-4} \text{ м}^2 / \text{сек} \quad (12)$
Количество теплоты (13)	$1 \text{ ккал} = 4,1868 \cdot 10^3 \text{ Дж} \quad (14)$
Удельная теплота (15)	$1 \text{ кал/г} = 4,1868 \cdot 10^3 \text{ Дж/кг} \quad (16)$
Удельная теплоемкость (17)	$(18) 1 \text{ ккал/кг} \cdot \text{град} = 4,1868$ $(19) 1 \text{ кал/г} \cdot \text{град} = 10^3 \text{ Дж/кг} \cdot \text{град} \quad (20)$
Масса (21)	$1 \text{ т} = 10^3 \text{ кг} \quad (22)$
Коэффициент теплообмена (23)	$1 \text{ кал/см}^2 \cdot \text{сек} \cdot \text{град} = 4,1868 \cdot 10^3 \text{ Вт/м}^2 \cdot \text{град} \quad (24)$
Вязкость обтекания (25)	$1 \text{ г/м} = 1 \cdot 10^{-3} \text{ кг/м} \quad (26)$
Удельная тепловая мощность (26)	$1 \text{ Вт/см}^2 = 1 \cdot 10^4 \text{ Вт/м}^2 \quad (27)$

Key: (1). Designation of values. (2). Coefficient for bringing to unity of SI. (3). Density. (4). $1 \text{ g/cm}^3 = 1 \cdot 10^3 \text{ kg/m}^3$. (5). $1 \text{ kg} \cdot \text{s}^2/\text{m}^4 = 9.80665 \text{ kg/m}^3$. (6). Pressure. (7). $1 \text{ bar} = 10^5 \text{ N/m}^2$. (8). $1 \text{ atm (tech)} = 9.80665 \cdot 10^4 \text{ N/m}^2$. (9). Dynamic viscosity. (10). $1 \text{ kgf} \cdot \text{s}/\text{m}^2 = 9.80665 \text{ N} \cdot \text{s}/\text{m}^2$. (11). Kinematic viscosity. (12). $1 \text{ St} = 1 \cdot 10^{-4} \text{ m}^2/\text{s}$. (13). Quantity of heat. (14). $1 \text{ kcal} = 4.1868 \cdot 10^3 \text{ J/kg}$. (15). Specific heat. (16). $1 \text{ kal/g} = 4.1868 \cdot 10^3 \text{ J/kg}$. (17). Specific heat. (18). $1 \text{ kcal/kg} \cdot \text{deg}$. (19). $\text{cal/g} \cdot \text{deg}$. (20). $\text{J/kg} \cdot \text{deg}$. (21). Heat-flux density. (22). $1 \text{ kcal/m}^2 \cdot \text{s} = 1.1630 \text{ W/m}^2$. (23). Heat-transfer coefficient. (24). $1 \text{ kal/cm}^2 \cdot \text{s} \cdot \text{deg} = 4.1868 \cdot 10^4 \text{ W/m}^2 \cdot \text{deg}$. (25). Water content of clouds. (26). Specific heat output. (27). $1 \text{ W/cm}^2 = 1 \cdot 10^4 \text{ W/m}^2$.

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